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THE RADIO SPECTRUM REQUIREMENTS OF BROADBAND POWER LINE TELECOMMUNICATIONS SYSTEMS

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This thesis is submitted in complete fulfillment of the requirements of the
Open University for the degree of PhD.

The Open University, Faculty of Technology
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ABSTRACT

There is concern among short wave (HF) radio users that broadband Power Line telecommunications (PLT) systems could cause serious interference to their services. The purpose of my research was to identify the factors that determine the performance of broadband PLT systems and to investigate how to maximise system performance while minimising the effect of PLT on HF radio systems. The study concentrates on the requirements for Access Band systems used to provide local loop service operating on 230/400V three-phase Low Voltage mains distribution networks.

The basis of the study is a comprehensive set of measurements made on Low Voltage mains distribution networks in the UK, mainland Europe and Australia.

The new approach to PLT band planning taken in this thesis uses Claude Shannon's information theory to predict the data capacity of arbitrary 3MHz sub bands. The results of the measurement programme are used to determine an optimum frequency band plan for PLT systems, taking account of the needs of the systems and the protection of other users of the HF spectrum. An example of how the proposed band plan can be used on a typical LV distribution network is included.

The use of the mathematical models with the results of the attenuation, noise and emission measurements show that it is possible to improve on both the frequency band plans proposed in current PLT standards and the non-standard frequency usage of many PLT trial systems. This will facilitate the achievement of competitive performance without causing undue radio interference, thus potentially making broadband PLT more acceptable to the HF radio community.

The choice of modulation and coding systems required to deliver the predicted performance in the presence of transient interference is also discussed.

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DECLARATION

The measurements on the Ipswich network were made in collaboration with West End Systems Ltd on behalf of Eastern Group Telecommunications and I had joint responsibility with the WES engineer for the design of the measurement strategy. The joint work was limited to the collection of the measurement data. All other work and the analysis reported in this thesis is original, except where acknowledged in the text or by reference. The work has not been submitted in support of an application for any other degree issued by the Open University or any other institution. None of the work has been published previously.

1. INTRODUCTION

Most governments believe that the ubiquitous availability of telecommunications services is essential to economic development. Good data communications are seen as particularly important to economic growth, so that governments are striving for the availability of affordable broadband services to all of their citizens, using competition to control costs. Particular emphasis has been placed on the local loop connecting the telecommunications customer to the operator's Point Of Presence, which relies upon the telecommunications service operator's plant such as individual telephone lines or a cable TV system. Governments have had considerable difficulty in 'unbundling' the local loop from the old monopoly telecommunications operators and are thus looking for alternative methods of provision to ensure competition.

With the privatisation of the UK Electricity Supply Industry in 1990, based on an act of Parliament passed in 1989, distribution network operators became free to participate in activities beyond the supply of electricity and many have looked at the provision of telecommunications services for additional revenue streams. This is also true outside the UK in those countries where electricity supply has been liberalised.

Because the electricity distribution system reaches all households and businesses, it has proved attractive to some distribution network operators as a potential telecommunications network. Early attempts to use the supply system for telecommunications focused on low data rate applications, such as street lighting control [Johns & Aylott 1967] and remote meter reading [Miura et al 1987]. But street lighting is now controlled by individual photocells at each lamp column and remote meter reading systems for domestic customers cannot compete economically with manual readings, although the 100kW plus market now uses public wireless data systems for remote meter reading to collect half-hourly data. PLT has also been used for tariff control and centralized meter reading within blocks of flats, where access for meter reading may be a problem [Baggott 1972]. Demand-side management systems using remote control of customer loads via the mains potentially have the capability of eliminating the need for spinning reserve and reducing the peak demand [Jennings 1995]. However, economic studies have failed to show a viable business case even when the Industry was integrated, so that the advantages would certainly not exist in the current market-driven environment. Because of the lack of any significant economic advantages of low-speed PLT systems they have not been taken up widely.

In recent years equipment has become available that can provide broadband data rates over electric power lines, typically offering speeds of one to four Megabits per second to subscribers. At the time of writing, according to the OPERA web site, *"It is estimated that more than 80 [access] PLC initiatives in more than 40 countries have been launched, worldwide, by electric utilities"* [Opera 2005]. However, broadcasters and other HF radio users are worried about the interference potential of such systems and there are no agreed standards on what constitutes harmful interference. This has led to a situation in which the radiocommunications users have expressed serious concerns over the development of PLT. The amateur radio position is made clear by a statement by the Radio Society of Great Britain in a paper to a European Union PLC workshop, in which it stated that "The society will take all measures open to it to oppose the introduction of mains HF signaling" [RSGB 2001] and its public position that "The question is, how will amateur radio be affected if access PLT is deployed on a commercial basis. On present showing it would be disastrous" [Claytonsmith 2003]. The American Amateur Radio Relay League (ARRL) has devoted a large section of its website to a campaign to "Stop the assault on ham radio" [ARRL 2005]. The position of the broadcasters is summarized by BBC R&D's reaction to the tests it

performed at Crieff in Scotland; "The forms of access PLT that were tested in Crieff were found to have demonstrable potential to cause interference to indoor reception of broadcasting in relevant bands" [Stott & Salter 2003]. These reactions by highly respected organisations raise the question of the extent and causes of the problem, which was the motivation for this research programme.

The study of broadband PLT Access systems covers many academic disciplines, as shown in fig 1.

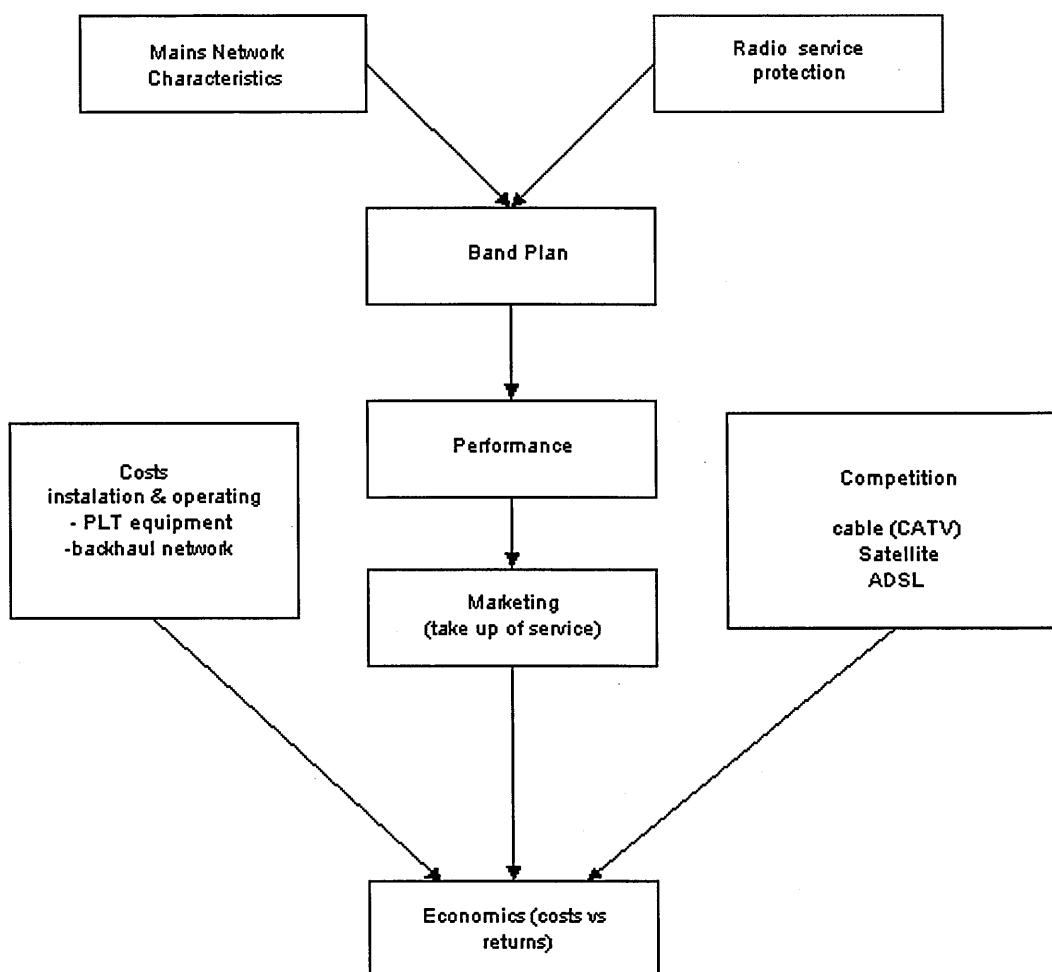


Figure 1 Factors affecting the planning of a broadband PLT Access system

Fig 1 shows that the performance of a PLT Access system is determined by the band plan, which must be based on the emission limits required to protect radio services, and the mains network attenuation and noise characteristics in the HF band. Having established the performance it is possible to compare PLT to its main competition (ADSL, Cable TV systems and satellite) and establish the likely take-up and the rental that can be charged. That will then allow an economic case to be made by comparing the estimated income stream with the

cost of installing and operating the system. This thesis only concerns itself with the issues highlighted in fig 1, and in particular the development of an appropriate band plan capable of providing competitive performance while minimising interference to radio services.

Much of the work done by standards bodies and other researchers in this field has been directed towards the measurement of the effects of deploying existing equipment, rather than starting from the basic characteristics of networks to derive optimum band plans and operating configurations. Thus the aim of my research programme is to show that the proper choice of band plan and modulation system will permit competitive data rates to be achieved reliably, and without radio interference, in the unusually harsh telecommunications environment of a LV mains distribution network.

1.1. Elements of this Research programme

The aim of this research programme was to undertake a theoretical examination of the factors affecting the performance of PLT systems in relation to their potential for radio interference. It has been necessary to make extensive measurements, sometimes using new techniques, to support the theoretical study. Important aspects of the research programme are as follows:

1. Actual attenuation measurements made on real LV distribution networks are used , rather than the output of computer models of arbitrary networks
2. The concept of the telecommunications link power budget is adapted for use in PLT systems, incorporating all the relevant parameters including emission limits
3. The variations in the characteristics of the LV networks are taken into account by the new method of averaging all the parameters relevant to the transmission performance of a PLT hop in 3MHz sub-bands
4. The contribution of ingress noise is examined in detail
5. The improvement in data rates within the emission limits as a result of using an incoming filter at a subscriber's premises is quantified.
6. Close attention is paid to the effect of diurnal variations in the ingress noise and system attenuation
7. The effect on band planning of the operation of PLT systems on adjacent LV networks is investigated.
8. The possible effects of intermodulation products (IMPs) of PLT signals that may be generated in LV networks is considered and a method of measuring the magnitude of IMPs is demonstrated.

This holistic, systems-based approach facilitates the full assessment of PLT system performance having due regard to its effect on radio systems.

1.2. Organisation of this thesis

Following this introductory chapter, this thesis is organised as follows:

Chapter 2 commences with an overview of the architecture of the UK electricity distribution system, including an assessment of the number of customers connected per substation at each voltage level. It then describes the architecture of a broadband PLT system, showing how it fits the electricity distribution system already described.

Chapter 3 examines the problem of signal radiation from telecommunications systems, relating this to basic concepts in EMC. The terms used in the standards are explained.

Chapter 4 reviews the standards applicable to PLT systems, including a comparison of the worldwide proposals for conducted and radiated emission limits to

protect radio services from PLT and other wired telecommunications networks

Chapter 5 examines the potential radio interference from broadband PLT systems, drawing on measurement data to establish the levels of emission from trial PLT systems. The requirements for the protection of radio services are compared with the proposed emission limits in the existing standards.

Chapter 6 provides details of the mathematical models derived from standard telecommunications theory that was used to predict the data throughput of PLT systems from the experimental data.

Chapter 7 deals with the measurement techniques required to provide the data necessary for use with the mathematical models.

Chapter 8 presents the results of the measurements made and includes a comparison of emissions measured in the trial systems with the emission limits proposed in the standards currently under development

Chapter 9 shows the outcome of using the results of the measurements and the mathematical models to derive an

effective band plan aimed at maximising data transmission rates with the minimum of interference to radio users.

Chapter 10 presents the conclusions and a critical review of the study, and sets out a path for future investigations into the subject.

2. SYSTEM ARCHITECTURE

This chapter describes the architecture of the power system and a typical broadband PLT system. It also provides details of the number of customers connected at each voltage level of the distribution system.

2.1. The UK Electricity Supply System

The architecture of the UK electricity supply system must be considered in terms of its commercial structure, which changed significantly at privatisation [chap 1], thus providing the incentive to develop broadband communications systems.

2.1.1.Commercial Structure

The electricity supply system has three basic elements:

- Generation
- Transmission
- Distribution

Since privatisation, these have been operated as separate businesses, which are all independent from electricity retailing. It is the distribution networks on which

broadband PLT systems are currently being trialed and deployed.

The national transmission system is operated by the Natioanl Grid Company (NGC), while the distribution networks are operated by what were first known after privatisation as the Regional Electricity Companies (RECs). Since privatisation these companies have changed ownership frequently and, in some cases, have combined into larger units covering several of the old REC areas.

2.1.2. Overview of the Complete UK Electricity System

Fig 2 shows the electricity system from power station to customer.

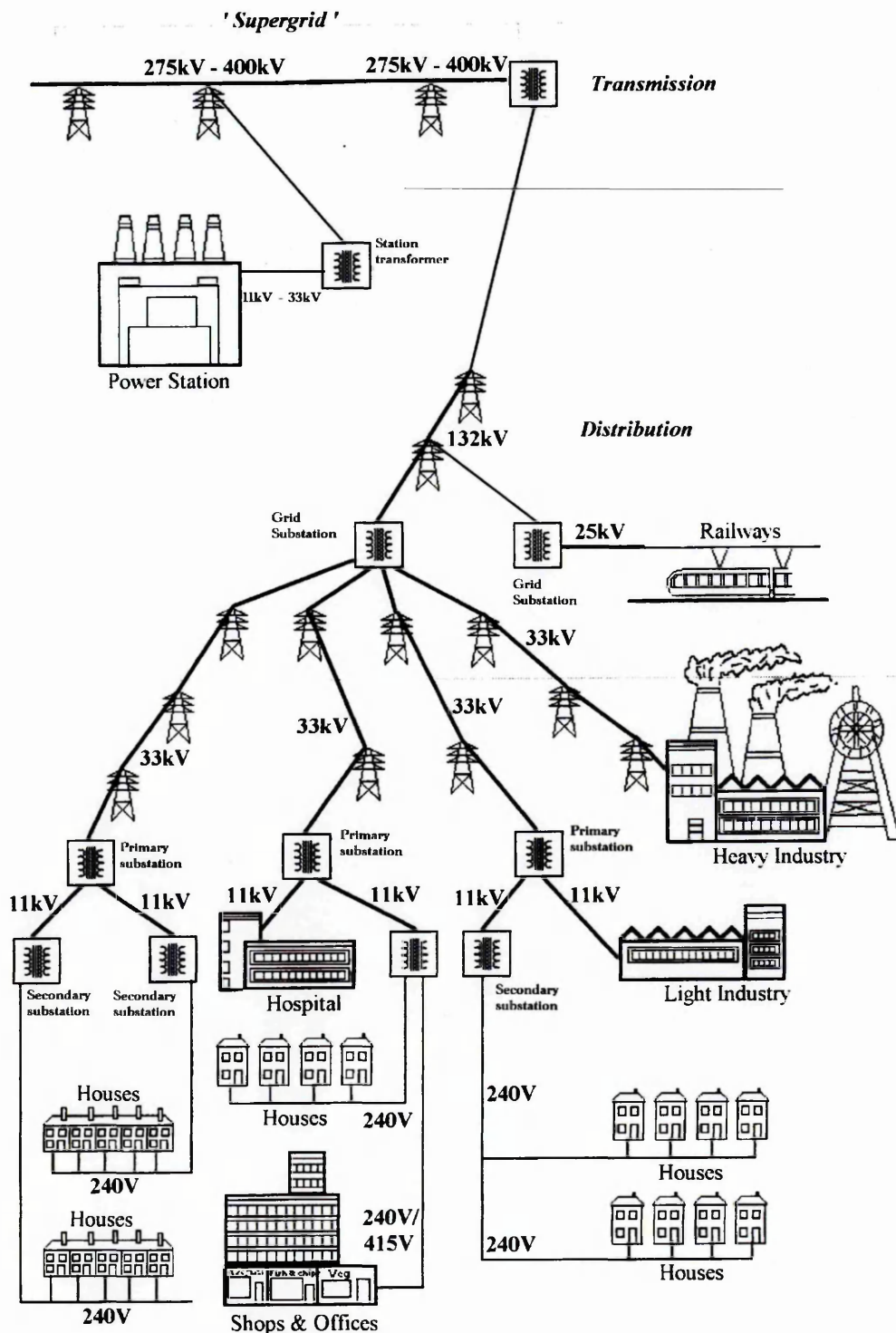


Figure 2 The electricity system [Morris, 2001]

2.1.3. The Transmission and Generation System

The top level of the electricity system is the transmission network, consisting of the 275kV and 400kV systems. The 275kV system was introduced in the 1950s to cope with increasing load and facilitate the construction of much larger power stations [Cochrane 1985, pp41]. The first level of the transmission system was the 132kV network, which was developed in 1927 by the Central Electricity Board (CEB) to "...co-ordinate the electricity supply in Great Britain..." [Hawks, undated, pp108], the supply having previously consisted of isolated networks associated with local generating stations. In the 1970s the assets and operational responsibilities for the 132kV system were devolved to the (then) Area Electricity Boards, as load growth had caused 132kV to be seen as a distribution voltage, rather than a transmission voltage.

With the Electricity act of 1957, the Central Electricity Board that operated the first transmission system soon became the Central Electricity Generating Board (CEGB), with responsibilities for all generating plant as well as the transmission network [Cochrane 1985, pp46]. The CEGB was disbanded in 1990, leaving the National Grid Company (now National Grid/Transco after NGC combined with the gas grid operator Transco in 2002) to operate the transmission system. At this time, the generating stations were given to three companies (National power,

Powergen and the nuclear station operator British Energy). Additionally, private generation was encouraged and was facilitated by allowing gas fired power stations to be built, and by sales of surplus "uneconomic" plant by National Power and Powergen.

2.1.4. The Distribution network

There are 12 distribution networks in the UK, each of which was run by its local Area Electricity Board and had its own design and construction standards dating from before nationalisation in 1947, although National standards have been used for later extensions.

2.1.4.1. Distribution Network Voltage Levels

The distribution network encompasses a hierarchy of voltage levels associated with the size of the loads served. A typical dual circuit 132kV line will support approximately 90MW of 'firm' capacity; both the line and the associated 'grid' substation being capable of supporting the load if one of the two circuits or transformers fails.

The next level of hierarchy usually operates at 33kV, with the 33kV/11kV transformers being located at the 'primary' substations. A typical primary substation has a firm capacity of about 25MW. Some distribution networks utilize other voltages at this level; both 22kV

and 66kV systems being typical of 1930's practice that are still in use today. It should, however, be noted that load density in cities and large towns is often too great to permit the use of these voltage levels, in which case the feed to the primary substation is a 132kV circuit with direct transformation from 132kV to 11kV. In the more rural areas, a typical primary substation will have six outgoing overhead 11kV feeds, while in central London a 60 panel 11kV switchboard is not an uncommon sight.

The lowest 'high voltage' level is the 11kV network. This is sometimes described as Medium Voltage (MV), although that term is not often used within the British Electricity Supply Industry. The 11kV network transports electricity from the 'primary' substations to 'secondary' substations where it is transformed down to 400/230V Low Voltage (LV) for use in shops and homes.

Voltage levels on the MV system have increased since the first AC electricity systems were installed, in line with the growth in load density associated with the greater use of electricity. Thus the old 3.3kV systems, a few of which were still in use until the 1960s, have now been replaced by 11kV, while "planning engineers [in Edf Energy] are considering the use of 25kV circuits to secondary substations to meet the load densities in

London" [conversation: author/Bob Jackson, system automation engineer, EdF Energy, November 2003].

For domestic customers and small shops, the final connection is provided by the 400/230V Low Voltage (LV) system, from a secondary substation owned by the distribution company. Customers using large loads are supplied at MV and own and operate their own secondary substations and LV networks. Therefore, large customers have no connection with the public LV distribution network.

2.1.4.2. Number of Customers Served by a Substation

The number of customers connected to a substation depends upon the load density, which varies considerably between urban and rural areas and also with the type of heating used in domestic buildings; estates using electrical heating having higher load requirements than gas-heated estates. An analysis of the number of customers per substation at each voltage level was made, based on data from the 1983 Handbook of Electricity Supply Statistics [ESI 1983 pp18], and is shown in table 1.

Table 1 Number of customers per Substation at Each Voltage Level
transformers

Area Board	customers	Primary	LV pole mounted	LV ground mounted	average customers per primary	average customers per secondary
London	1808000	162	0	11317	11160	160
South Eastern	1765000	257	12034	16623	6868	62
Southern	2200000	630	24052	22828	3492	47
South Western	1125000	374	32824	10260	3008	26
Eastern	2674000	585	31272	22018	4571	50
East Midlands	1962000	438	18910	12357	4479	63
Midlands	1972000	292	31891	12952	6753	44
South Wales	856000	227	30358	6423	3771	23
Merseyside and North Wales	1266000	657	28452	8803	1927	34
Yorkshire	1870000	421	15470	13600	4442	64
North Eastern	1332000	281	13267	8033	4740	63
North western	1998000	448	14575	14900	4460	68
overall averages					4973	59

Because of the age of the data (which is no longer published), the table refers to 'Area Boards'. For the purposes of this study, the average number of customers per substation at each voltage level is of interest, and that will only have changed because of the connection of new houses to existing networks, which will have minimal effect. The data are therefore considered to be adequate for the purposes for which they will be used in this thesis.

2.1.4.3. LV System Operation

As LV networks are the most likely to have PLT deployed on them, it is important to understand the operational constraints imposed upon the PLT system by the power system operations necessary to meet regulatory commitments of providing a continuous power supply to customers. This section describes those constraints by reference to the typical LV network configuration shown in fig 3.

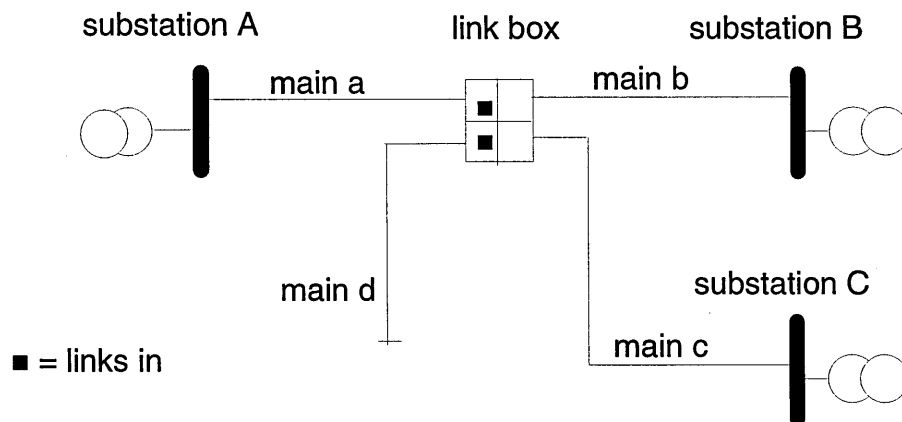


Figure 3 LV network configuration [Brannon 1995, p4]

Fig 3 shows the basic arrangement of a residential network with three secondary substations A, B and C. Each substation has a number of feeders supplying the houses around it, but only those feeders associated with interconnections to other substations are shown. Mains a, b and c are interconnectors that meet in a link box;

they are also used to feed the houses that are distributed along their routes. Because of the geographic layout, it is convenient for main D to be fed from the link box, rather than directly from a substation.

The link box is an underground connection box into which the cables are jointed. It has terminals connected to each cable conductor, allowing the same phases on different cables to be interconnected using removable links that are inserted with an insulated tool. The normal running condition for the network is shown; the box acts as an 'open point' between the substations and the links to mains b and c are normally left out. The links are in between cables a and d so that cable d receives its normal feed from substation A. If a fault occurs that shuts down one of the substations, supplies can be restored by inserting links. For example, if the HV supply to substation B fails it is possible to restore supplies to customers on main b by removing fuses at substation B to isolate the main, then fitting links into the box to connect main b to substation A or substation C. A further option is to leave the feeder fuses in at the failed substation and open the transformer links to isolate the transformer from the busbars. It is then possible to feed further customers from substations A or C via the busbars of substation B. However, that type of

backfeed is often impractical because of excessive voltage drop or other load related problems. This type of network rearrangement is used as a short-term solution while repairs are carried out.

It is clear that the type of change of running conditions described above must take precedence over any communications requirements and must be carried out promptly to avoid or minimize the penalties associated with guaranteed supply standards, which require suppliers to compensate customers for supply interruptions that exceed the time limits specified by the regulator. This means that any PLT system must be able to cope with unexpected changes to the topology of its physical layer, which is a challenge in terms of both transmission standards and network management.

The majority of underground LV networks in the UK are operated as described above. However, the old London Electricity Board did operate 'solid' networks, in which substations ran in parallel. It is understood that this practice may have been abandoned due to safety problems associated with excessive fault level; such operation also requires the use of directional overcurrent protection at the substations to avoid backfeeding HV faults from the LV network, which makes the substations excessively complicated.

Similar configurations are applied to urban overhead networks where the substations are closely spaced. In that case, the underground link box is replaced by a 'section pole' on which the conductors on either side terminate on separate insulators, so that they are not connected through. To restore supplies under fault conditions a linesman visits and fits temporary connections between the wires on each side of the pole. This feature is less likely to be available in rural areas because of the greater distances between substations, many of which are pole mounted and may only feed a single house or a small group of houses.

2.2. PLT Networks

Before entering into detailed discussion of PLT systems, it is essential that the configuration of such systems be fully understood. This section describes the PLT system architecture from the head end, which provides the content, to the subscriber modems.

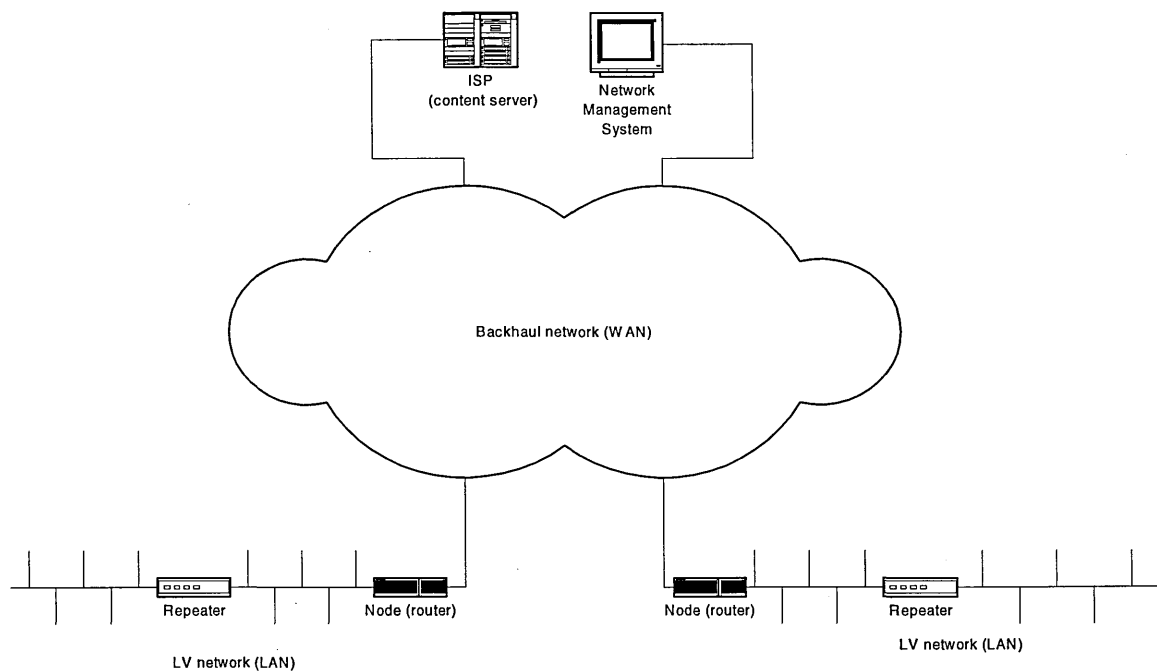


Figure 4 PLT system configuration

Fig 4 shows the configuration of a PLT system serving two LV networks, which, in terms of a data network, are effectively Local Area Networks (LAN). These are analogous to a LAN used in an office, where a number of workstations are connected to a single cable system and share the bandwidth; contention control mechanisms controlling access by each user. In the PLT case each LV

network is served by a node, which is usually located at the feeding LV substation. The node equipment has routing capability and includes the modems and couplers for connection to the LV network. A LV network may require one or more repeaters to overcome network losses, as shown in the drawing, which may also have routing capability to cope with LV network reconfiguration under power system fault conditions. The nodes are connected to the content server or head end via a Wide Area Network, known in cable TV (CATV) parlance as the backhaul network. The head end will also support a network management system, providing the capability of monitoring and controlling all elements of the PLT system, including the nodes, repeaters and subscriber modems. The node equipment may also incorporate a DHCP server, which is required to provide an IP address to the subscriber when they connect to the network. If not included in the node this facility will be part of the head-end equipment.

2.2.1. The Backhaul Network

The backhaul network is the Wide Area Network (WAN) that connects the LV network LANs to the head end. It is an important element in determining the performance of a PLT system. A number of options exist for the provision of the backhaul network, which depend upon the service offered to subscribers and the resources available to the distribution company operating the PLT network. The

backhaul network options are examined in the following sections.

2.2.1.1. Fibre Optic Networks

Some distribution companies have installed fibre-optic networks to support their telecontrol, operational and corporate voice and data networks. Some have also offered their optical networks to commercial users, sometimes on a 'dark fibre' basis. Such optical networks are typically designed to high standards, often being configured in self-healing rings using SONET/SDH technology. Unfortunately, these networks do not usually reach down to the secondary substations where the PLT nodes would be located, but stop at the 33kV voltage level, at the primary substations.

2.2.1.2. Private Pilot Cables

In major towns it is common to find private pilot cables linking secondary substations to their feeding primaries and to each other. These pilot cables were laid to provide unit protection for the power system. The cables used typically have three protection cores (often 7/.029 in²) and four thinner communications pairs. Some companies have experimented with the use of these cables for wideband data transmission, using DSL technology. It is potentially possible to achieve data rates of 1.544/2.048Mbps at ranges of up to 12000 ft using two or

four wires [Held 2000, table 3.1 pp64] or even up to 36000ft on AWG 24 wire if a HRE (HDSL Range Extender) is used [Held 2000, pp75]. This type of arrangement would provide a convenient way of extending the backhaul network from an optical node at a primary substation to the PLT mode at a secondary substation.

2.2.1.3. MV Power Network Backhaul Solutions

Experiments are in progress with the use of PLT over the MV network for backhaul [Issa & Devaux, 2004]. This would be a convenient option if there was an optical network to the primary substation, because the MV network links the primary and secondary substations. Work carried out in France by EdF suggests that data rates of the order of 8Mbps - 10Mbps will be possible [ibid]. Such high data rates are possible because underground MV networks are fully screened, with no building wiring connected. This means that in addition to a lack of radiating mechanisms to propagate interference the ingress noise is low and there are no signal reflections from service taps, so that the attenuation per unit distance is less than that of LV networks.

One problem with MV backhaul is that the available MV bandwidth would be shared between all the nodes connected to the primary substation; to separate the bandwidth on different feeders is potentially difficult due to the need to use filters fitted into the MV switchgear at the primary substation. The aggregated bandwidth needed

depends upon the number of LV networks connected to a primary substation and the data rate it is required to achieve on the LV networks. This is illustrated in table 2, which is derived from table 1 and shows the aggregated backhaul capacity requirements at a primary substation with data rates of 2Mbps, 40Mbps and 200Mbps on the LV networks. No allowance has been made in this table for bandwidth reduction based on contention between substations because contention between users already exists on the LANs, where the available data capacity is shared between all users on the LV network connected to the same node. The acceptable overall contention ratio could alter the maximum MV data capacity, and may alter across the network if, for example, business users were offered lower contention rates than residential users.

Table 2: Estimate of required data capacity on MV backhaul systems

average customers per primary	average customers per secondary	secondaries per primary	total required backhaul capacity per primary (Mbps)		
			2Mbps	40Mbps	200Mbps
			LV	LV	LV
11160	160	70	140	2800	14000
6868	62	112	224	4480	22400
3492	47	74	148	2960	14800
3008	26	115	230	4600	23000
4571	50	91	182	3640	18200
4479	63	71	142	2840	14200
6753	44	154	308	6160	30800
3771	23	162	324	6480	32400
1927	34	57	114	2280	11400
4442	64	69	138	2760	13800
4740	63	76	152	3040	15200
4460	68	66	132	2640	13200
4973	59	93	186	3720	18600

It can be seen from table 2 that even if the data capacity of the LV PLT networks is restricted to 2Mbps the aggregated data capacity required at the Primary substation is 324Mbps in the worst case (South Wales). While there may be some use for MV PLT in linking secondary substations, it must not be seen as a panacea for solving all backhaul problems.

2.2.1.4. Public Network Solutions

If the distribution network operator has no private telecommunications network that could be used to reach the PLT nodes, the only solution is to use a public network. The options are considered below.

2.2.1.4.1. *Frame Relay*

Frame relay services, such as Framestream [JSR 2005], are often used for connection to the Internet and support data rates of up to 2.048Mbps. Although this capacity is similar to that of T1 circuits, such as BT's Megastream, frame relay is often preferred because of the different way of calculating the line rental, which is based upon bandwidth and not distance. It is preferred to ADSL for backhaul applications because the frame relay service is uncontended and synchronous (ie it supports the same bandwidth for both upstream and downstream transmission and is not shared with other users).

2.2.1.4.2. *Satellite*

Some ISPs now offer a 2Mbps satellite connection and satellite services such as VSAT can provide economical point-to-point circuits with data rates of 2Mbps, or up to 8Mbps via some satellites [Eutelsat 2004]. While it may be difficult to accommodate the necessary dish antenna at some secondary substations, at least one distribution company (SSE) is using VSAT in its PLT backhaul network. In the configuration used by SSE the satellite terminal is located at a convenient central point and connections are provided to the nodes using BT EPS8 (two-wire, wires only) circuits running HDSL¹. Using VSAT, the backhaul network connects to the distribution

¹ When this arrangement is used the slave substations must be in the same BT exchange area as the satellite master

company's head end, which provides a connection to the Internet and may also provide dedicated content for the PLT system.

The network management system is connected directly to the PLT network via the head-end equipment.

An alternative option is for the distribution company to use a satellite ISP to provide the Internet connection, with the distribution company taking no part in the content provision. In that case, the PLT network management could connect to the remote routers and subscriber modems via the Internet.

The configuration of a PLT system using satellite backhaul is shown in fig 5, which shows the two alternative head-end configurations. Here, one satellite remote terminal is shown supporting a local PLT network and networks 1 & 2 are connected back to the satellite terminal location using leased lines. Network 3 is shown connected to its own satellite terminal, with no slave networks. Choosing between providing a dedicated satellite network and using a satellite ISP is purely economic, while the connection of the PLT nodes combines a number of economic and engineering considerations, including the practicalities of fitting dish antennas at secondary substations.

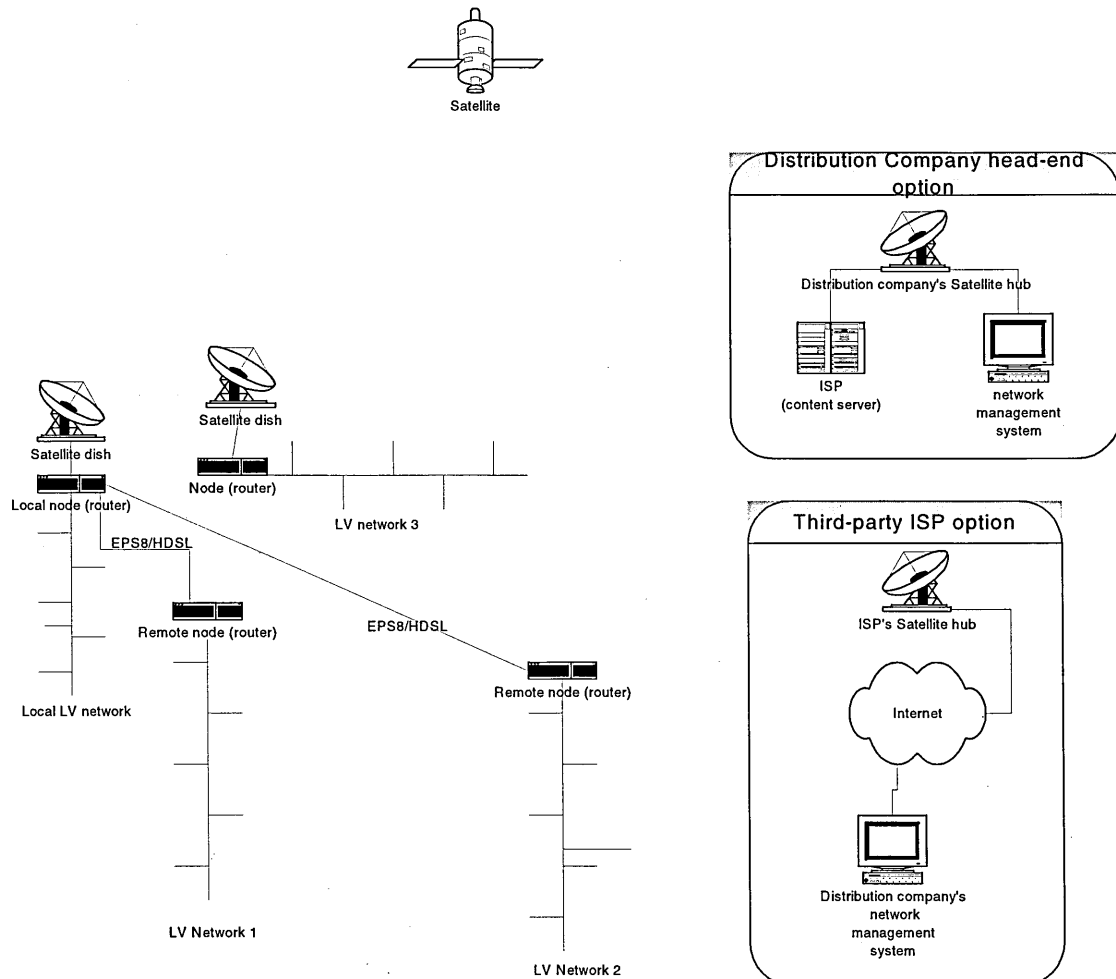


Figure 5 Satellite backhaul network configuration

2.2.1.5. Estimating the Number of Subscribers on a LV PLT Network

The economics of the backhaul network provision are related to the number of subscribers to the PLT service. Table 1 shows that the average number of customers connected to a secondary substation is 59, but this includes rural areas where a 'substation' may be a pole mounted transformer serving less than five houses [Bell & Meadows 1962 pp8]. Given an estimated ADMD of 5kVA and a typical ground-mounted transformer size of 500kVA, it is realistic to assume that the number of customers

connected to the type of network on which PLT is most likely to be used is 100. Using CATV terminology, the number of customers 'passed' is thus taken as 100.

The other important parameter is the take up of the service, which is the percentage of customers passed who actually sign up as PLT subscribers. Some available statistics for the end of Q1 2004 [Analysys 2004] help to provide guidance on the possible take-up rates:

- Cable modem data systems are available to 45% of UK households (55% are passed by cable TV)
- 43% of UK households have a choice between DSL and cable broadband
- broadband is available to 87% of UK households
- 13.1% of UK households subscribe to broadband (3224731 lines)

Given the above information, it is unlikely that the take-up rate of broadband PLT will exceed 13.1% of customers passed. This means that a maximum of 13 customers are likely to subscribe per LV substation, based on a broadband subscription rate of 13.1% of the 100 households passed by the PLT system subscribing to the service.

2.3. Summary

This chapter has examined the architecture of the supply system and the PLT system, and the network arrangements and operational constraints resulting from a need to meet guaranteed standards for the regulated business of electricity supply. It has considered various options for the PLT backhaul network. An estimate of the number of subscribers that can be expected to require connection to an underground network has been provided, based on UK conditions. In the next chapter, the mechanism of signal radiation from wired systems is considered, this being a key topic in the deployment of PLT systems.

3. SIGNAL RADIATION FROM WIRED SYSTEMS

Before looking in detail at PLT systems, it is necessary to consider the mechanisms by which wired telecommunications systems radiate radio signals. This chapter provides an overview of the basic EMC theory in sufficient detail to facilitate understanding of the review of PLT standards.

3.1. General Principles

Wired communications systems intended to carry radio frequency signals normally use one of two types of cable:

- Balanced two-wire line
- Coaxial cable

Balanced two-wire lines for HF communications normally consist of open wires, with consistent spacing from each other and distance from other metallic objects and earth, to maintain the balance by equalizing stray capacitance. Twisted pairs are balanced two-wire circuits intended primarily for audio (telephone) signals. Coaxial cable consists of an inner conductor surrounded by a dielectric material inside a conducting outer sheath, which may be

continuous or woven depending on the quality of the cable.

A balanced line is fed with a differential mode signal, which is balanced with respect to earth, as shown in fig 6.

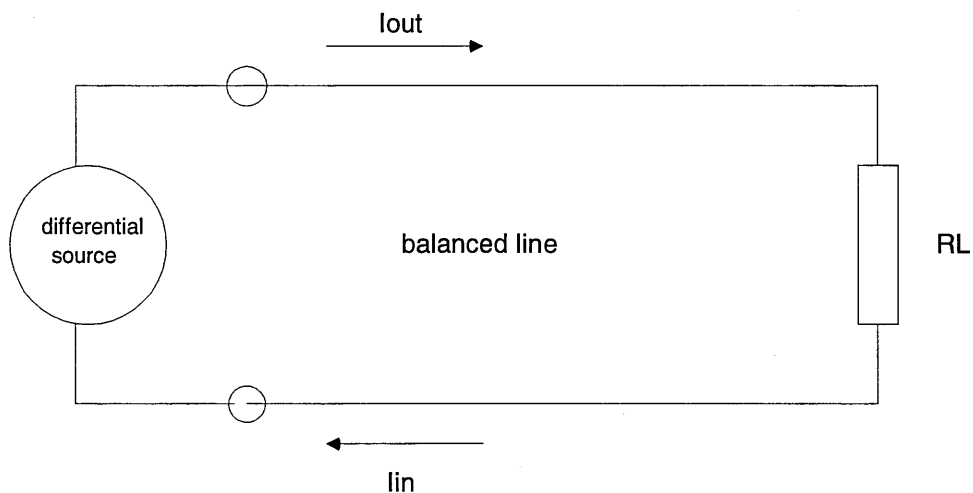


Figure 6: Balanced transmission line

The line is terminated in a load RL , which is matched to the characteristic impedance of the line, which is also matched by the source impedance. If the line, the source and the load are perfectly balanced current I_{out} will be the same as current I_{in} . This means that the electromagnetic fields surrounding the conductors will have the same magnitude but opposite polarities; hence they will cancel out and the net emission of power from the line will be zero. If the line or its terminations become unbalanced I_{in} and I_{out} will no longer be equal in magnitude, and the line will radiate. The difference

between the two currents, $I_{out} - I_{in}$ is known as the *common mode current* (aka antenna mode current) and flows in the earth between the source or load and the point of unbalance, rather than in the line.

The difference between the differential voltage applied to the line and the (unwanted) common mode voltage between the line and earth is called the Longitudinal Conversion Loss (LCL) and is defined in equation 1.

Equation 1 calculation of longitudinal conversion loss

$$LCL = 20 \times \log \left(\frac{\text{developed common mode voltage}}{\text{developed differential mode voltage}} \right) \text{ dB}$$

Fig 7 [Williams & Armstrong 2000, pp160, fig 7.5] shows how stray impedances can convert differential mode signals to common mode. In this equivalent circuit the components C_c are stray capacitances between the conductors of the line and earth, while Z_s and Z_L are stray impedances in the source and load respectively. It is stated by Williams and Armstrong that these capacitances will dominate, but that inductive effects will also be involved, especially where the line passes close to other metallic structures. These inductive effects are represented in fig 7 by the component L_c .

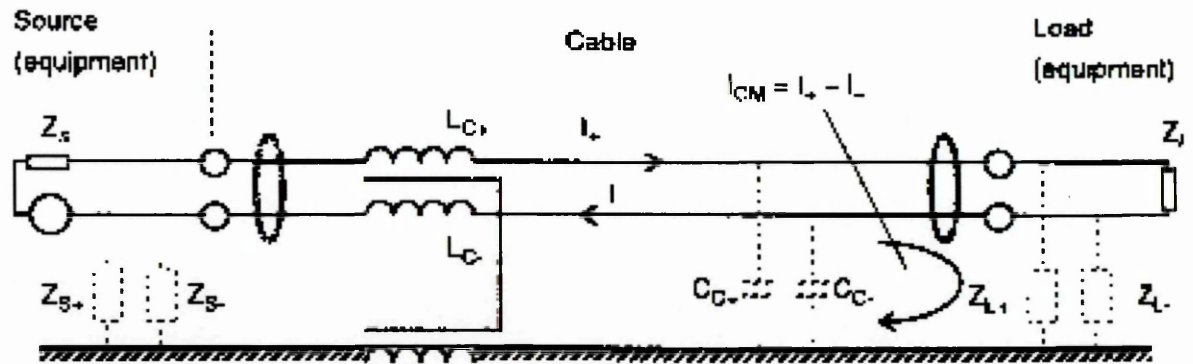


Figure 7: Differential to common mode conversion mechanisms

[Williams & Armstrong 2000]

Although most RF feeders now use co-axial cable, computer Local Area Networks have moved away from co-ax (IEEE 802.3/1986) to twisted pair (10BASE-T) in both screened and unscreened formats [Madron 1994 pp237-241]. Unscreened cable is the most common implementation on the grounds of cost and compatibility with telephone wiring. The adoption of twisted pair wiring for LANs can be seen as a retrograde step because the type of unbalance shown in fig 7 leads to high levels of signal radiation, as anyone who has tried to use a portable band 2 VHF receiver in an office with a 100Mbps LAN can testify.

3.2. PLT Systems

PLT uses mains wiring intended for 50Hz power delivery and thus no attempt has been made to optimize it for HF transmission. While the balance of a modern twin and earth mains cable intended for use in houses and small shops may, of itself, be fairly good because the geometry

is controlled by the manufacturing process, its installation will mean that stray capacitances result in unbalance to earth. Wiring in large buildings often consists of single conductors carried in screened metal trunking, so that pairs of conductors comprising a circuit can take slightly different routes, leading to inherent unbalance. An example of how this can occur is shown in fig 8, in which the random spacing of the cables to each other and to earth is clearly visible. Such an installation could be expected to exhibit a poor LCL.



Figure 8: Example of poor wiring practice in a large building

In addition to the likelihood of unbalance being caused by the installation of the wiring, there are two other reasons why PLT systems are unlikely to behave in the same way as balanced telecommunications feeders. The first is that lighting circuits separate the live and neutral conductors at the ceiling rose, extending the live wire down to a switch. This means that for each fixed lighting point there is a substantial length of what, in signaling terms, is a single wire circuit [Stott 2003, pp25]. Power circuit wiring practice varies considerably between countries but in the UK ring circuits are used in domestic premises, as shown in fig 9.

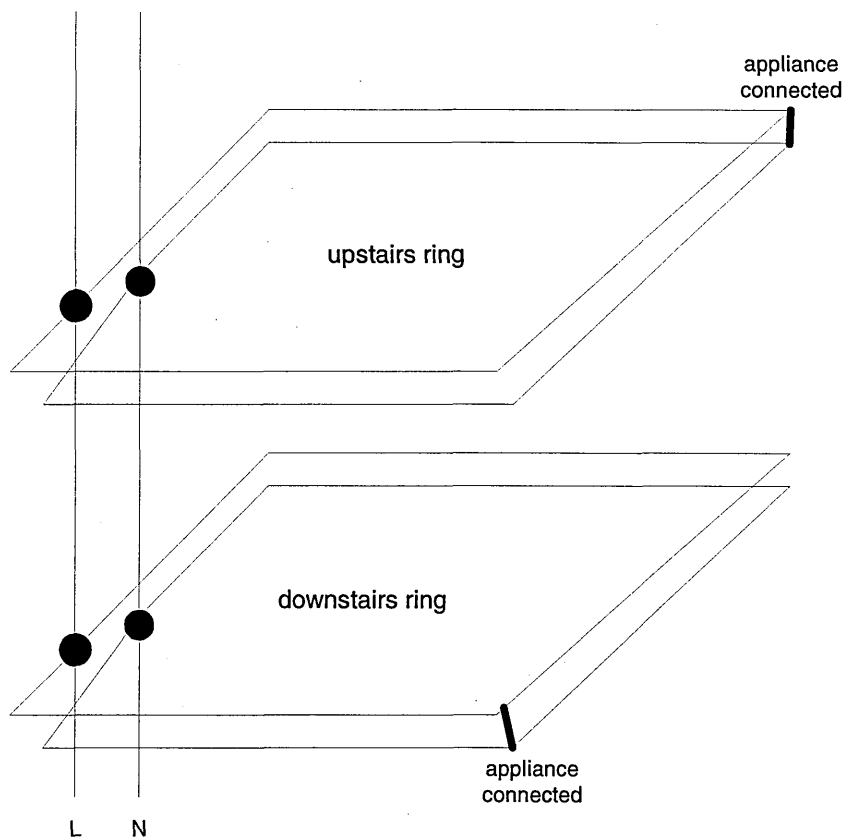


Figure 9: UK ring main circuit configuration

With no appliances connected, each ring circuit consists of a loop connected to the live conductor and a separate loop connected to the neutral conductor, these being contained in the same cable in domestic wiring. When an appliance is introduced, the live and neutral conductors are joined via a low impedance depending on the power consumption of the device and its internal circuitry. This impedance may be very low at HF, especially if the appliance contains capacitors for interference suppression. If, due to fortuitous coupling effects, the HF impedance of the phase conductor is different to that of the neutral conductor on the same side of the loop between the feed and the point at which the appliance is connected, the HF signals on the live and neutral conductors may flow around different sides of the ring circuit, thus converting it to a loop antenna. In this case, emission is possible without common mode currents, the situation being analogous to a series of loop antennas connected to a balanced feeder. In a multi-storey building the loops will be stacked, leading to the potential for formation of an antenna with a complicated Radiation Pattern Envelope and considerable gain.

Measurements made for this research programme [Brannon 2005] and, independently, by the BBC [discussion during Q&A session following IEE presentation, see Brannon 2005], have failed to find a meaningful correlation

between LCL and emissions in trial PLT systems, thus suggesting that the PLT signal radiation mechanism is not associated with common mode current.

The definition of LCL is specified in ITU-T recommendation G.117 [ITU 1996], "Transmission aspects of unbalance about earth", which also specifies another parameter, Transverse Conversion Loss (TCL). The difference between LCL and TCL is the method of measurement; LCL requires the injection of a common mode signal and measurement of the resulting differential mode signal, while for TCL the measurement and injection points are reversed, so that the common mode signal caused by a given injected differential mode signal is measured. While the standards applicable to wire-line communications systems tend to concentrate on LCL, it is pointed out by some authorities that "These methods [LCL and TCL] can be applied to all telecommunications systems, such as transmission lines, equipment or their combinations. However, the TCL is the most important value with respect to being able to determine the amount of longitudinal (or common mode) voltage caused by unbalances in the system, which is the principle [sic] cause of radiated disturbances. Once TCL is known, one would be able to calculate the asymmetric voltage at a given amplitude of the symmetrical signals. Then, this can be used to estimate the strength of the radiated

emissions with an appropriate model" [Hrasnica et al, 2004, pp64]. It is believed that the preference for measuring LCL is to avoid difficulties resulting from common mode ingress noise, which might over-ride the signal resulting from the injected test voltage when the conversion loss (TCL) is high. A measurement carried out as part of this research programme suggested that the TCL is the same as the LCL for a given network, as would be expected because a passive network should exhibit reciprocity of its transfer function.

3.3. Summary

This chapter has provided an introduction to signal radiation from wired systems and the special case of PLT systems. This provides the background knowledge needed to understand the currently available standards relating to broadband PLT, which are critically reviewed in the next chapter.

4. REVIEW OF PLT STANDARDS

There are currently no specific standards for broadband PLT, although there is a large amount of activity in the standards development bodies. This chapter therefore reviews the current state of the art in PLT standardization.

4.1. PLT Standards Bodies

The standardization process for PLT apparatus is shown in fig 10 [Newbury 2005].

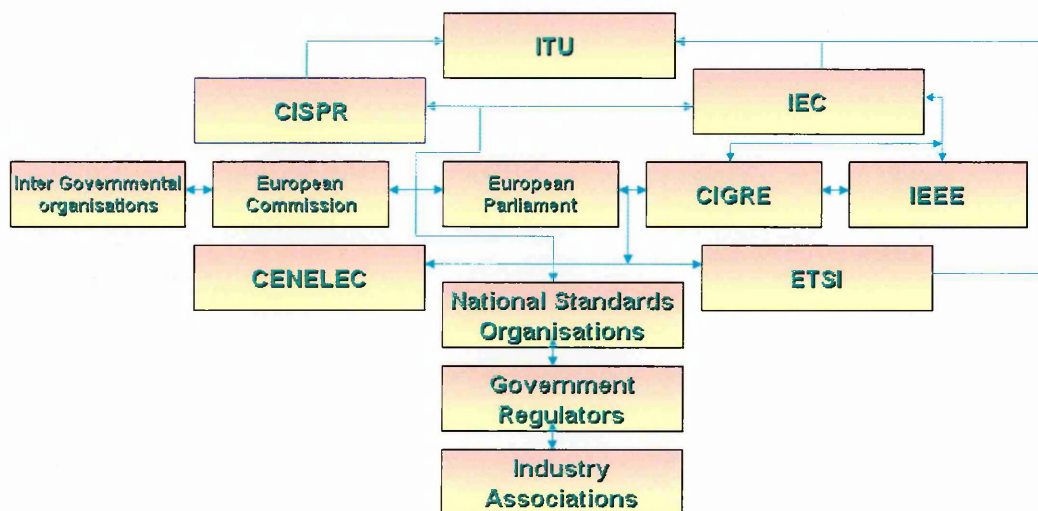


Figure 10: PLT Regulatory and Standardisation framework [Newbury 2005]

The bodies referred to by the acronyms in fig 10 and their functions are identified and listed in table 3

Table 3 Bodies involved in PLT Standardisation and Regulation

acronym	English Name of body	Aim/function
CENELEC	European Committee for Electrotechnical Standardisation	European electrical standards
CIGRE	International Council on Large Electrical Systems	"Worldwide exchange of engineering knowledge and information" [CIGRE 2005]
CISPR	International Special Committee on Radio Interference	Sub-committee of IEC for the "protection of radio services in the frequency range 9kHz to 400GHz" [CISPR 2005]
IEC	International Electrical Commission	"leading global organization for international standards in..electrical technologies" [IEC 2005]
IEEE	Institute of Electrical and Electronic Engineers	Worldwide electrical standards
ETSI	European Telecommunications Standards Institution	European ICT standards
ITU	International Telecommunications Union	"...coordination of global telecommunications networks and services" [ITU 2005]

The European and international standardization bodies produce standards that are used by the national standardization bodies (eg the British Standards Institute in the UK) to produce national standards, as well as being used in their own rights. In addition, because PLT has the potential to interfere with radio services, the National radio regulators (eg OFCOM,

formerly the Radiocommunications Agency, in the UK) are also involved in producing regulatory standards, which are used to determine whether or not the apparatus is at fault if an interference complaint is received. It should be noted that there is little latitude for making national spectrum allocations for the PLT service; the HF radio spectrum is very full and it is not possible to make provisions without reference to the World Administrative Radio Conferences

4.2. Standards

The standards applicable to PLT fall into two categories:

- Conducted emission standards
- Radiated emission standards

Conducted emission standards define the amount of power that a device (in this case a PLT modem) is allowed to inject into the network to which is it connected. These tend to be associated with certification of the device for CE marking and are product standards. Radiated emission standards are more complicated because they must take account of the characteristics of the network to which the device is connected. As stated previously, regulatory standards are used for enforcement of the radio regulations.

There is a general consensus that standards should be devised that treat all types of wired media carrying communications signals alike, so that the standards under development are required to apply to all the following systems:

- POTS (Plain Old Telephone Service)
- DSL (Digital Subscriber Line - all variants)
- CATV (Community Antenna TeleVision - aka cable TV)
- PLT (Power Line Telecommunications)
- BPL (Broadband Power Line - US name for PLT)

This chapter continues with a review of the conducted standards and the regulatory limits.

4.2.1. Standards for Low Frequency PLT Systems

The operation of Low Frequency PLT systems used for control and remote meter reading is specified by CENELEC, the main documents being the EN 50065 series, which specify the frequency bands to be used and the permitted injection voltages, as well as factors associated with the construction of specific modules, such as filters.

4.2.2. Broadband PLT

Because broadband PLT is relatively new, there are currently no standards comparable with the LF specifications, although they are under development. In

addition, because of the worries about the possibility of radio interference from PLT systems, a number of PTTs are developing standards defining the maximum emission limits for PLT systems. This section examines the currently available standards that affect the operation of broadband PLT systems.

4.2.2.1. Band Plan

A band plan for broadband PLT systems is specified in ETSI TS 101 867 [ETSI 2000]. The objective of this band plan is to provide compatibility between systems used within buildings and 'access' systems used to connect a subscriber to a public data network. Two alternative plans are specified, as follows.

4.2.2.1.1. Band Plan for First Generation Equipment

The basic band plan splits the HF spectrum as shown in fig 11 [ETSI TS 101 867 sec 5.1]. More specifically, Power Spectral Density (PSD) limits are imposed, as shown in fig 12 [ETSI TS 101 867 sec5.2]. The PSD mask, and hence the band plan, is not applicable if an incoming filter is used to provide separation between the systems.

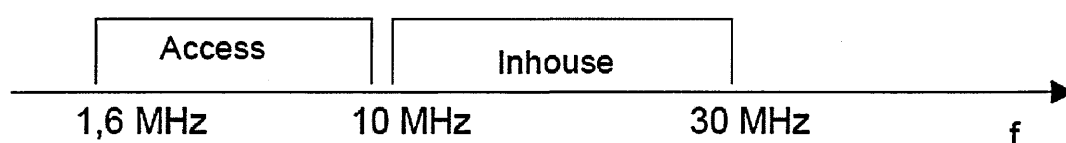


Figure 11: ETSI First Generation PLT Band Plan [ETSI TS 101 869]

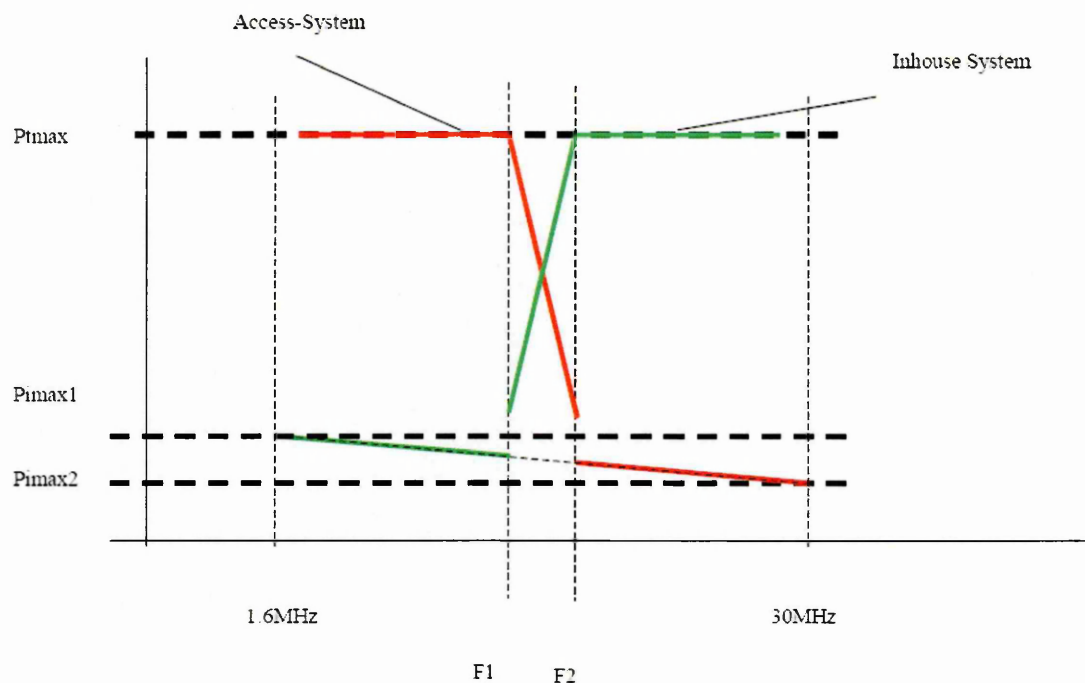


Figure 12: ETSI Access/in-house Co-existence PSD Limits [ETSI TS 101 869]

Referring to fig 12:

- $F1 = 9.4\text{MHz}$
- $F2 = 11\text{MHz}$.
- $P_{\text{imax1}} = -105\text{dBm/Hz}$
- $P_{\text{imax2}} = -125\text{dBm/Hz}$

The Pimax levels are said to be representative of the average noise floor level. The systems shall not transmit at a level exceeding the Pmax level appropriate to their frequency band, but these levels were not defined in the 2000 version of the standard.

4.2.2.1.2. Band Plan for Second Generation Equipment

Second generation equipment is permitted to use a more flexible band plan using dynamic frequency assignment principles. The second-generation band plan is shown in fig 13 [ETSI TS 101 867 sec 6.1].

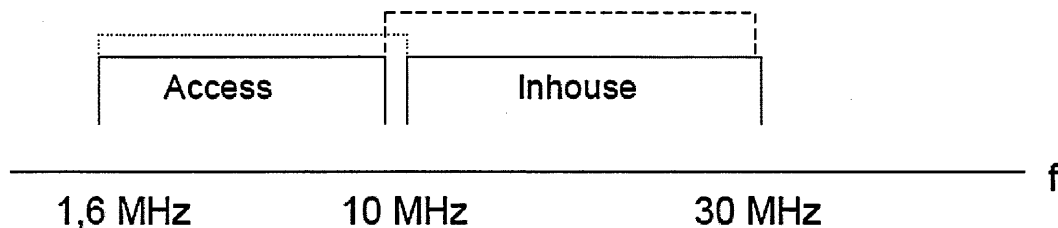


Figure 13: ETSI second generation band plan [ETSI TS 101 869]

Equipment operating to this band plan is required to be capable of using a common signaling channel defined in TS 101 869. When in-house equipment is not present or is not using the 11MHz to 30MHz band, the access equipment is permitted to use it and vice-versa. The common signaling channel ensures that the equipment only uses the appropriate band if the other type of equipment wishes to communicate.

4.2.2.1.3. Comments on ETSI TS 101 867

The standard does not specify the reasons for the choice of frequency for the division of the spectrum between access and in-house systems, so that it is not clear whether the split is arbitrary or based on good engineering practice. The possibility that a filter

would be fitted to segregate access and in-house systems appears to be based upon a false hope. While access systems would be installed by the distribution system operator or their agent, in-house systems are most likely to be purchased by a householder as a plug and play, shrink-wrapped item. For an in-house system a filter is therefore unlikely to be fitted because:

- The householder would not wish to go to the expense of fitting a filter, having purchased PLT equipment to avoid the cost of additional wiring
- The filter would need to be fitted at the service intake, so that only a meter operator or distribution company could fit it
- At a house that took the access PLT service a filter could be fitted when the access system was installed, such a filter providing other advantages to the access system. However, in-house equipment used at houses that did not subscribe to the access PLT service could cause interference to the access system, because they would not have an incoming filter.

On this basis it seems clear that there must be a band plan that defines access and in-house spectra and that plan should be based upon sound engineering reasons, not an arbitrary split. It is further necessary to consider

the possible need to sub-divide the access band into upstream and downstream sub-bands to avoid the near/far problem [Cooper and Gillem 1998 pp279] whereby a receiver attempting to resolve a weak signal may be blocked by a physically close transmitter in the same band. The division of the spectrum into upstream/downstream sub-bands would also facilitate the use of real-time frequency translating repeaters that do not reduce data throughput, as opposed to store-and forward repeaters with their input and output in the same band, which by their operation each halve the available data rate.

4.2.2.2. Conducted Limits

Currently, the only document that can said to be applicable to signal injection to a mains network from a broadband PLT modem is CISPR 22:1997, published in the UK as BS EN5022:1998, "Information Technology Equipment Radio Disturbance Characteristics - Limits and Methods of Measurement" [BS EN55022 1998]. This *product standard* specifies the limits of conducted disturbances associated with the mains ports and telecommunications ports of equipment. The frequency range covered by the document is 9kHz to 400GHz.

CISPR 22 divides equipment into two classes:

- Class B equipment, being "...intended primarily for the domestic market..." [BS EN55022:1998 para 4.1]
- Class A equipment, which is "... a category of all other ITE which satisfies the class A limits but not the class B limits" [BS EN50022:1998 para 4.2]

Class A equipment is required to carry a specified warning label indicating that it may cause radio interference that would require the user to "take appropriate measures" to eliminate.

From this it seems that in-house PLT systems that would be purchased by users without special knowledge of radio interference would be categorised as Class B, while access band equipment could be covered by Class A, because it would be installed and operated by the operator of the distribution network.

A further discussion document [CISPR/I/89/CD] proposed changes to CISPR 22 and introduced the concept of a 'multipurpose port' meant for handling mains supply and telecommunication signals, which is clearly applicable to PLT modems.

The relevant limits are specified in tables 1, 2 and 3 of CISPR 22 and are shown in table 4, which also shows their

source. The limits shown are for measurement with receivers using a Quasi-Peak (QP) demodulator.

Table 4 CISPR 22 Conducted Disturbance Limits

Class	Port Type	Frequency Range (MHz)	Limit (dBµV QP)	Source [BS EN55022: 1998]
A	mains	0.5 - 30	73	Table 1
	comms	0.5 - 30	87	Table 3
B	mains	0.5 - 5	56	Table 2
	comms	5 - 30	60	Table 2
A	Multi-purpose	0.5 - 30	87	[CISPR I/89/CD]
B		0.15 - 0.5	84	
		0.5 - 30	74	
	Relaxation	6.0 - 30	84	[EN55022 Table 4 note 3]

In table 4, where a range of values is quoted in the source document the maximum value is taken. The row titled 'relaxation' is a provisional relation of the telecommunications port B limits for " high speed services having significant spectral density in this band" [BS EN55022 1998 table 4 pp8].

Because the speciality of the CISPR 22 group is radio interference, the intention of the limits set in the standard is to limit radio frequency emissions to a level that will protect radio services. According to EMC theory (3.1), the emissions from a differentially connected source are related to the common mode current (aka antenna mode current) and the magnitude of this current in relation to the injected disturbance is

determined by the LCL. For this reason, CISPR 22 also specifies an LCL of 80dB between 150kHz and 1.5MHz, and 80dB to 55dB decreasing linearly with the logarithm of frequency between 1.5MHz and 30MHz, based on "...an approximate representation of the LCL of a typical telecommunications circuit..." [EN 55022:1998 note 1 pp15]. It is generally accepted that the LCL of a mains network falls considerably short of that figure and a number of measurement programmes have been instituted to find a more appropriate value. However, the assumption that LCL is any indication of the emission characteristics of a mains distribution network or house wiring is open to question, as mentioned in section 3.2.

The proposals in CISPR I/89CD clearly indicate the document's nature as a product standard. Because current PLT equipment needs injection voltages higher than those specified in CISPR22 to achieve the required operating distances and data rates it is proposed to increase the limits, without reference to the effect on radio services. The implications of this need to be established so that the potential effects of the I/89CD proposal can be assessed.

4.2.2.3. Radiated Emission Limits

Radiated emission limits are required for the protection of radio services. They are set by the PTTs of

individual countries and provide guidance for the investigation of interference complaints. If, as a result of a complaint, a source of interference is found to be radiating at above the specified level, action can be taken under the radio acts (UK) to shut down the service and possibly to apply legal penalties to the user. Such limits are defined as a maximum electric field strength at a specified distance from the installation.

When broadband PLT trials first started in the UK (c 1995), it was suggested by the UK Radiocommunications Agency that the then current standard for emissions from Cable television systems, MPT1320, should apply to PLT. However, a working group was set up to review the standards applicable to emissions from all types of wired media (LAN, ADSL, CATV and PLT), and that resulted in the production of a new draft enforcement standard, [MPT1570 2000], intended to cover the frequency range 9kHz to 300MHz. Similar standards for application to PLT have been produced by the Netherlands, Germany and the USA, although the limits proposed vary greatly and the measurement distances specified are not consistent. The issue of measuring distance is quite important because the limits required to protect sensitive radio equipment are low. Therefore, it is difficult to measure the level of emissions at the limits with practical antenna systems

capable of deployment where PLT would be used, because the signals to be measured may be below the noise floor of the measurement equipment.

Further information on the derivation of all the field strength limits displayed on graphs in this thesis is given in appendix A. Fig 14 shows a comparison of the proposed emission limits, normalised to the 13m measurement distance used for some of the measurements considered in this thesis to facilitate meaningful comparisons of relative levels.

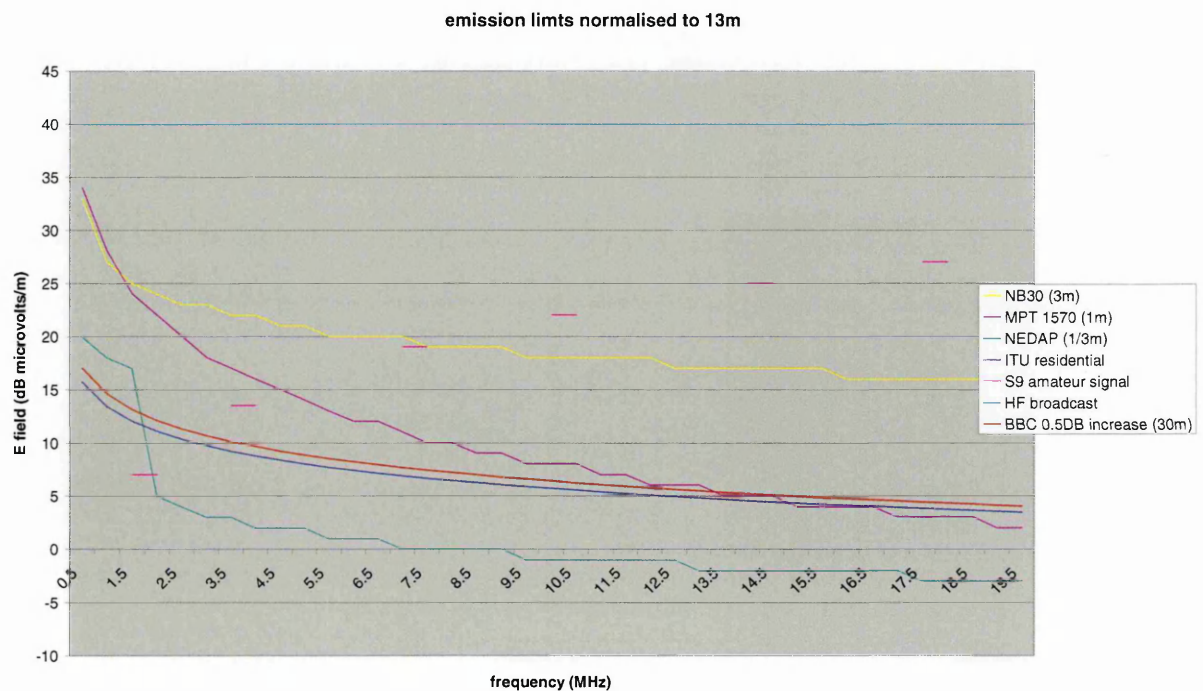


Figure 14 Comparison of radiated emission limits at normalised distance

The captions for fig 14 show the specified measurement distances for the various standards, but the limits are all normalised to 13m to facilitate comparison (13m was

chosen for compatibility with some of the earlier measurements associated with this research). The distance chosen is not important but normalization to a standard distance is the only way in which the limits can be compared). The NEDAP (Netherlands) limit is unusual in that a measurement distance of 1m is specified between 0.5MHz and 1.5MHz, while the measurement distance is 3m between 1.5MHz and 30MHz. The ITU-R residential noise level is not a limit but is an estimate of the expected background noise in a residential area; therefore it does not have an associated distance. The process of normalizing the limits to 13m uses equation 2:

Equation 2 Normalisation of emission limits

$$field_strength_{13} = field_strength_d + 20 \times \log(d / 13)$$

where d is the specified measurement distance in metres and the field strengths are expressed in dB μ V/m. This equation is applicable to the near field case and the normalisation distance of 13m is within the near field for frequencies below 3.7MHz, assuming a point source radiator. I have not attempted to be more accurate in my usage of the near and far field equations because the changeover distance is dependant on the size of the radiating element, which will depend upon the particular installation and is not easily determined.

The countries of origin of the limits are as shown in table 5.

Table 5: Countries of Origin of Limit Proposals

Country	Limit
Germany	NB30
Netherlands	NEDAP
United Kingdom	MPT1570

In addition to the proposed limits and the ITU-R residential noise floor curve, the graph also shows the expected signal levels for broadcast and amateur signals, being two typical users of the HF bands. The broadcast field strength is taken from a BBC report [Stott 2003] and the derivation of the amateur field strength is given in appendix A.

Comparing the limits, it can be seen that the German NB30 limit is the highest at all frequencies above 1.5MHz, being matched by MPT1570 below that frequency. The Dutch NEDAP limit is the lowest, being below the ITU-R residential noise floor at frequencies above 1.5MHz when corrected to 13m measurement distance. It should be noted that at 13m all of the limits are below the 30dB μ V/m noise floor of a typical wideband HF loop measuring antenna, which is why much closer measurement distances are specified.

4.3. Summary

In this chapter, the ETSI co-existence band plan, the CISPR 22 conducted limits and the worldwide emission limit proposals have been considered. It has been shown that these standards contain a number of anomalies, and that there is little international agreement on the limits needed to protect radio services. The proposed limits are compared with an estimate of the signal strengths encountered in radio reception on the HF bands. In the next chapter, the issue of potential radio interference from PLT systems is considered in detail, in the context of the proposed standards and the results of measurements made by other workers in the field of research.

5. POTENTIAL RADIO INTERFERENCE

This chapter considers the potential of Broadband PLT systems for causing radio interference. It looks at the theoretical implications of the standards reviewed in the previous chapter and provides details of the conclusions reached by other workers in the field.

5.1. Theoretical Implications of the Proposed Limits

In fig 14, typical signal levels were shown for broadcast and amateur signals, as well as the proposed limit lines for PLT emission. In comparing the limits with the radio signals that they are intended to protect, the following can be seen:

- Broadcast signals are not protected by NB30 at any frequency, given that even commercial telephony requires a signal to noise ratio of 30dB for acceptability by users of the service
- MPT1570 provides an acceptable degree of protection only above 7.5MHz
- NEDAP provides 35dB of protection at frequencies above 1.6MHz.

While the NEDAP proposal appears to be adequate for protecting broadcasting services it should be remembered that fig 14 shows the equivalent limit at 13m, while the

casual listener will be using a radio with an attached whip antenna within the wiring system to which the PLT is connected. Even with outside antennas, as required for an interference complaint to be valid under UK rules, a separation distance of 13m would be difficult to achieve in normal domestic circumstances.

In the case of amateur signals, it can be seen that even at 13m separation only the 20m (14MHz) and 16m (18MHz) amateur bands would be protected by NB30. Although the S9 amateur signal shown for the 30m (10MHz) band is above NB30 the 5dB of C/I (Carrier to Interference) ratio provided by NB30 is insufficient even for communications quality speech. Of course, the levels plotted are the strongest for which amateur equipment is calibrated and usable amateur signals that are near the noise floor of the receivers will be considerably below those shown on the graph. In practice, this means that for proper protection of amateur services the limits should be lower at the amateur bands.

An alternative proposal, made by the BBC [Stott 2001] and based on a European Broadcasting Union (EBU) proposal, is that the limit be set for a noise floor rise due to PLT of 0.5dB with respect to the ITU-R residential noise floor prediction, measured at a distance of 30m from the PLT installation. This limit is also shown in fig 14 and

----- can be seen to serve its intended purpose of protecting most radio services. However, the 160m amateur band (1.8MHz) is not protected because a S9 signal (appendix A) has a field strength below the ITU-R residential noise floor if a resonant dipole is used; albeit unlikely to be the case in a built-up area as the antenna would be 90m long.

5.2. Results of Measurements by Other Bodies

By 1998 the first trials of broadband PLT were under way in the UK, organised in Manchester by NOR.WEB, a subsidiary of the (then) North Western Electricity (later to become United Utilities). Because of fears of radio interference from the system, the (then) Radiocommunications Agency set up a meeting to which potential developers of broadband PLT and radio users were invited. Because of my involvement in a broadband PLT trial, I was invited to the first meeting, which was attended by a total of 33 people, possibly 25 of whom represented HF radio users. The membership of that meeting was refined and subsequently became the RA Power Line Carrier Expert Group, established in 2001 with representatives of PLT manufacturers and potential PLT and DSL system operators, the Radio Society of Great Britain, the BBC, British Telecommunications (BT), the Civil Aviation Authority (CAA) and the Ministry of Defence (MOD). The group's remit was to produce a

regulatory standard for DSL, cable TV and PLT systems, and it was responsible for the production of the MPT1570 standard [MPT1570 2000] to which reference has already been made. The work of the group included a field measurement programme, carried out by the RA, dealing with the effects of the available equipment. The results of this measurement programme are detailed in the group's final report of 2002 [RA 2002]. A typical example of the results obtained is shown in fig 15.

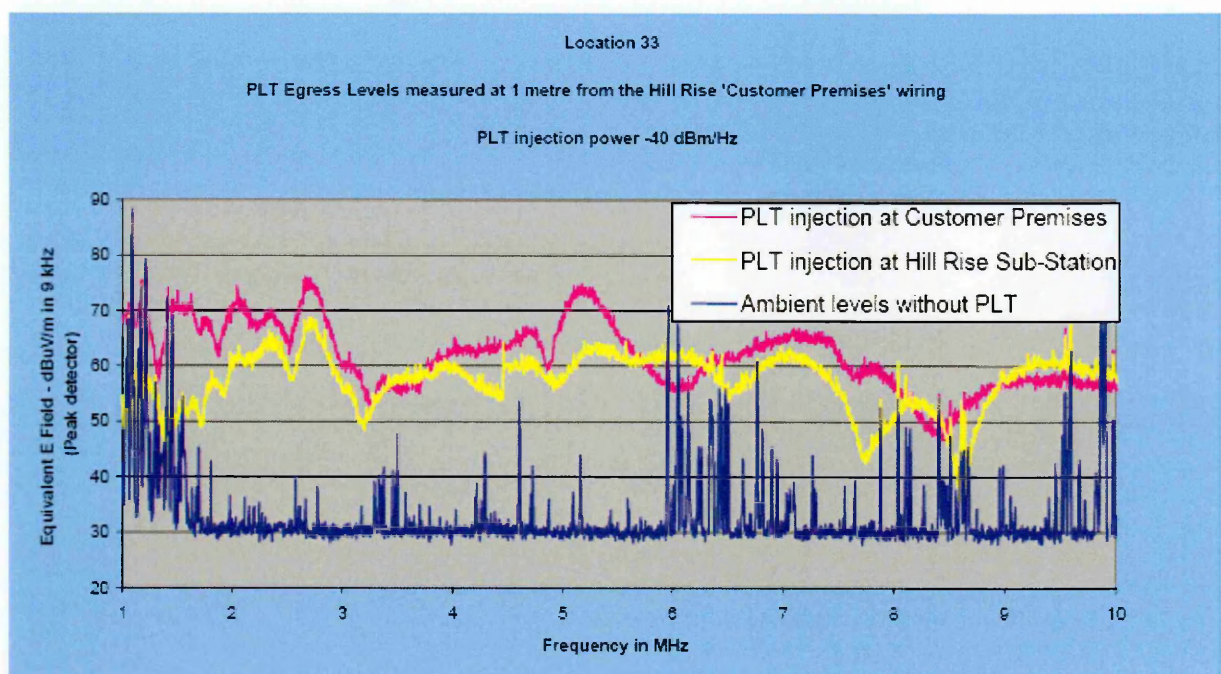


Figure 15: Example of results of PLT measurements from the RA report [RA2002]

It can be seen that the signal levels measured are considerably in excess of the 40dBuV/m broadcast field strength coverage area limit [fig `4], showing that the system measured had the potential to cause disruption to radio services. This was also true of a number of other measurements made on different systems by the RA and,

independently, by the BBC. A disadvantage of all the studies undertaken was that no attempt was made to link the radiated results to the injected power.

One proposal put to the RA working group was to "Provide chimney exception for DPL (sic) allowing up to 50dB μ V/m at 10m within the frequency bands 2.2 - 3.5MHz and 4.2 - 5.8MHz, conditional upon provision of geographic exclusion and emergency switch off arrangements" [NOR.WEB 1999]. This could not be accepted because it would have placed unacceptable restrictions on international planning of the HF band.

5.3. Summary

This chapter has examined the interference potential of broadband PLT equipment in terms of the currently proposed wireline emission limits and the results obtained by the (then) Radiocommunications Agency (RA) PLT Expert Working Group. Not only are many of the proposed limits set too high to protect many radio services, but the emissions measured by the RA exceeded the proposed limits. The next chapter presents the telecommunications theory needed to understand the factors governing the operation of a PLT system.

6. TELECOMMUNICATIONS THEORY

In order to produce the performance models needed to fulfill the aims of this study it is necessary to adapt standard telecommunications theory. All radio links are designed on the basis of the link power budget, which is applicable to any form of communications link, from HF radio to EHF satellite radio links, and even optical fibre circuits. These models have been adapted for PLT to derive the signal to noise ratios at the receiving modems, which facilitates the calculation of the maximum available data rate under conditions of steady state noise, using Shannon's information theory. This section describes the models used later in this thesis [chap 9]. In addition, the effects of transient interference and how they can be alleviated by the use of suitable modulation and coding systems is discussed. The phenomenon of intermodulation and its potential effects on a PLT system is explained and a method of comparing the interference potential of PLT systems working on different networks is suggested.

6.1. Power Budgets for Access PLT Systems

The concept of a link power budget facilitates the calculation of the received power from a knowledge of the available transmission power and the losses in the transmission medium between the transmitter and receiver.

In the case of a PLT system, the transmission power is determined by the emission limit and the emission characteristics of the building or network in which the modem is deployed.

Power budget diagrams for the downstream, upstream and repeatered downstream cases are presented in this section. In each case, movement from left to right across the diagram implies increasing distance from the source, so that the cable attenuation is shown as a sloping line to indicate the relationship between signal level and distance. Some options for access system operation require the fitting of an incoming filter and the effect of such filters is incorporated into the power budget diagrams. The filter attenuation can be set to zero if a filter is not used. Power budget equations are derived from the diagrams.

6.1.1. The Incoming Filter concept

In the power budget diagrams that follow, reference is made to the use of an incoming filter as an option for improving transmission performance. An example of how such a filter might be applied is shown in fig 16. The input side of the filter is connected directly to the service intake Live and Neutral conductors, at the point on the building side of the service fuses to which the meter is normally connected. The meter is then transferred to the output side of the filter. The modem

is connected to the input side of the filter, so that it receives the PLT signals from the main without attenuation. The filter has a low-pass characteristic so that it passes the 50Hz mains current and blocks the HF signaling frequencies. This is an advantage in reducing the emissions from the local modem and reducing the locally produced ingress noise, thus aiding both upstream and downstream transmission.

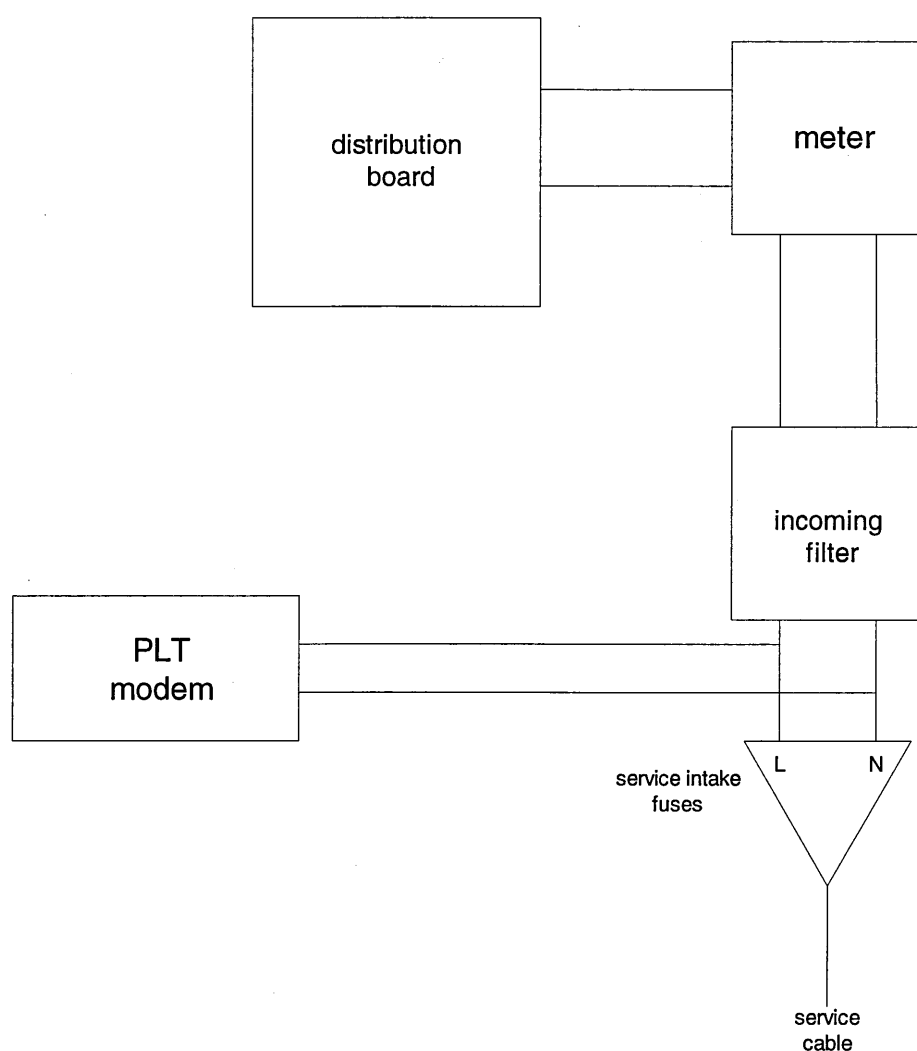


Figure 16: Use of an incoming filter

An incoming filter will need to be able to pass the 100A continuous full-load current of a large domestic or small

shop installation without overheating, and will need to be capable of passing around 35kA for up to 50 μ s without physical destruction while the fuse blows if a short circuit occurs on the meter tails or customer mains switch. This prospective fault current assumes a fault level of 25MVA at the substation busbars and a location adjacent to the substation [Tew 2005]

6.1.2. Downstream Power Budget

The downstream power budget of fig 17 shows the derivation of the signal to noise ratio at the subscriber's modem as a result of transmissions from the node, which would normally be located at the feeding substation. The emission limit is used as the datum to determine the maximum injection power from the transmitting modem. The relationship between the power injected and the emissions is given by the k factor at the injection frequency [section 7.1.5.2]. In the case of underground networks the PLT equipment at the node will be well screened and therefore the power injected to the network by the modem is limited by the emissions from the radiating structure closest to the node, the effect of which is slightly reduced by the cable attenuation between the node and the radiating structure, and possibly by an incoming filter if the radiating structure is a building at which the PLT service is used. Of

course, in reality the limiting radiating structure may be further away, depending on the ratio of the k factors of the various radiating objects. At the receiving modem the signal to noise ratio is determined by the difference between the signal received from the node and the ingress noise; the latter being reduced by the attenuation of the incoming filter if one is fitted.

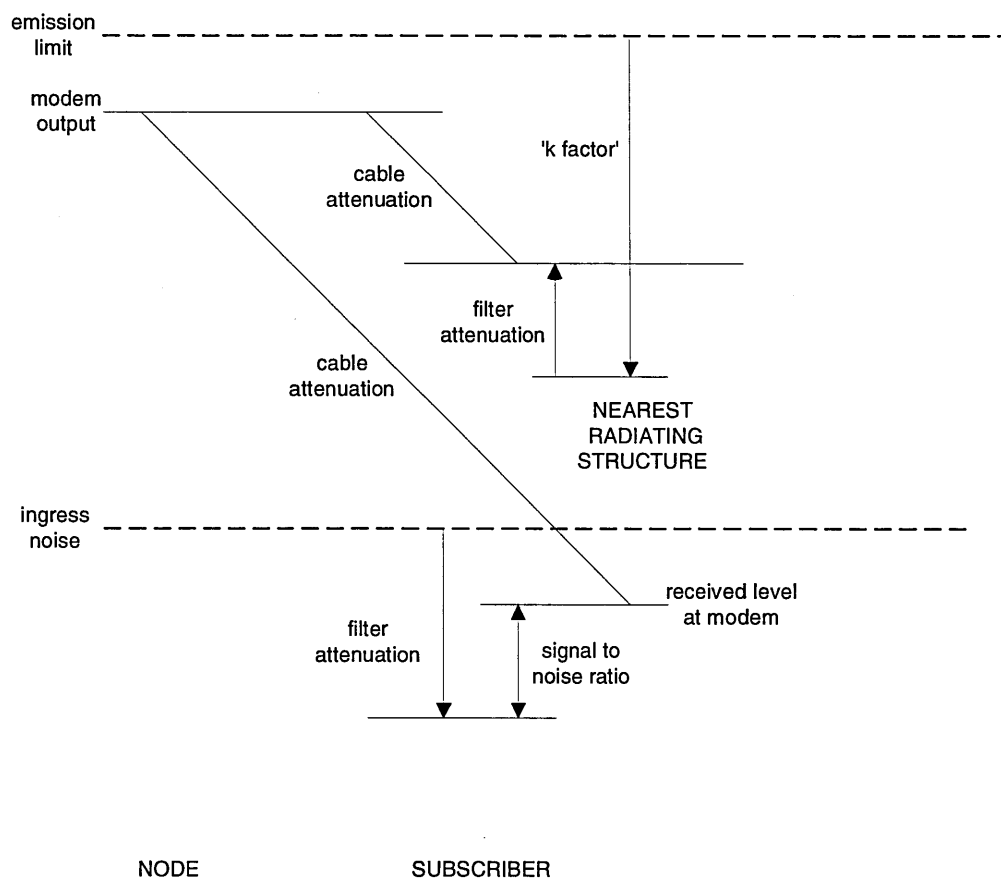


Figure 17: downstream power budget

From the power budget diagram, the signal to noise ratio at the subscriber house can be seen to be represented by equation 3:

Equation 3: downstream power budget

$$\text{SNR} = E_L - k + \text{attf}_1 + \text{attc}_1 - \text{attc}_2 + \text{attf}_2 - \text{ingress}$$

Where:

- E_L is the average emission limit
- k is the average k factor
- $attf_1$ is the attenuation of any incoming filter at the house closest to the node
- $attc_1$ is the attenuation of the cable between the node and the closest house to the node
- $attc_2$ is the attenuation of the main between the node and the subscriber house
- $attf_2$ is the attenuation of any incoming filter fitted at the subscriber house
- 'ingress' is the ingress noise level at the subscriber house. If a filter is used the value of the ingress noise is taken to be the higher of the ingress at the house minus the filter attenuation or the network noise as measured at a link box on the system (the latter of which is normally the limiting factor).

All of the above quantities are expressed in dBm in the same measurement bandwidth and are average values for the sub-band for which the capacity is being investigated.

6.1.3. Upstream Power budget

The upstream power budget is shown in fig 18.

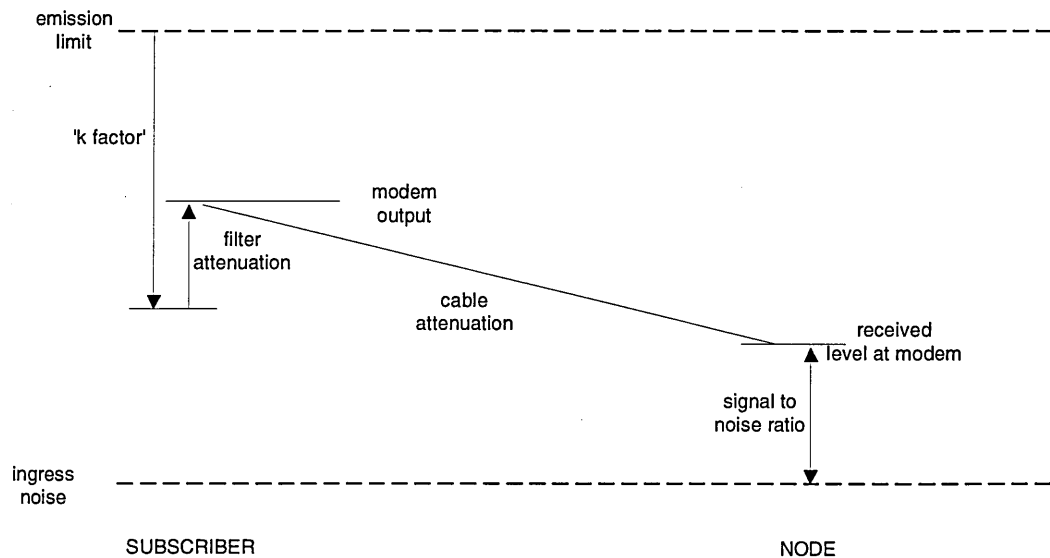


Figure 18: Upstream power budget

Again, the emission limit is used as a datum from which the modem injection power is determined. From the power budget diagram, the signal to noise ratio at the node can be seen to be given by equation 4:

Equation 4: Upstream power budget

$$\text{SNR} = E_L - k + \text{attf} - \text{attc} - \text{ingress}$$

Where:

- E_L is the average emission limit
- k is the k factor of the subscriber house
- attf is the attenuation of any incoming filter at the subscriber house
- attc is the attenuation of the main between the node and the subscriber house

- 'ingress' is the ingress noise level at the node
(usually the substation busbar)

All of the above quantities are expressed in dBm in the same measurement bandwidth and are average values for the sub-band for which the capacity is being investigated.

6.1.4. Downstream Power Budget with repeater

In some cases it may not be possible to achieve the desired performance throughout the network, because beyond a certain distance the requisite signal to noise ratio cannot be achieved within the regulatory limits. In that case the use of a repeater may be considered. The power budget for the downstream case with a repeater is shown in fig 19.

Fig 19 shows the case with and without the repeater, using the assumption that the system would be adjusted for the required data rate regardless of the emissions limit. The modem power output at the node is determined as for the downstream case of fig 17. Without the repeater the modem output would be such that it would result in radiation above the specified limit, marked as 'excess emissions' on the power budget diagram. The part of the diagram that shows the same network operated with

a repeater assumes that the repeater would be located as far as it can be from the node, while still meeting the data rate requirements. At this point the signal to noise ratio is defined on the diagram as the 'minimum workable'. Although the ingress noise is shown at the same level at the subscriber and the repeater, it should be noted that in a practical situation the ingress noise at the repeater may be lower than at the subscriber, due to network attenuation.

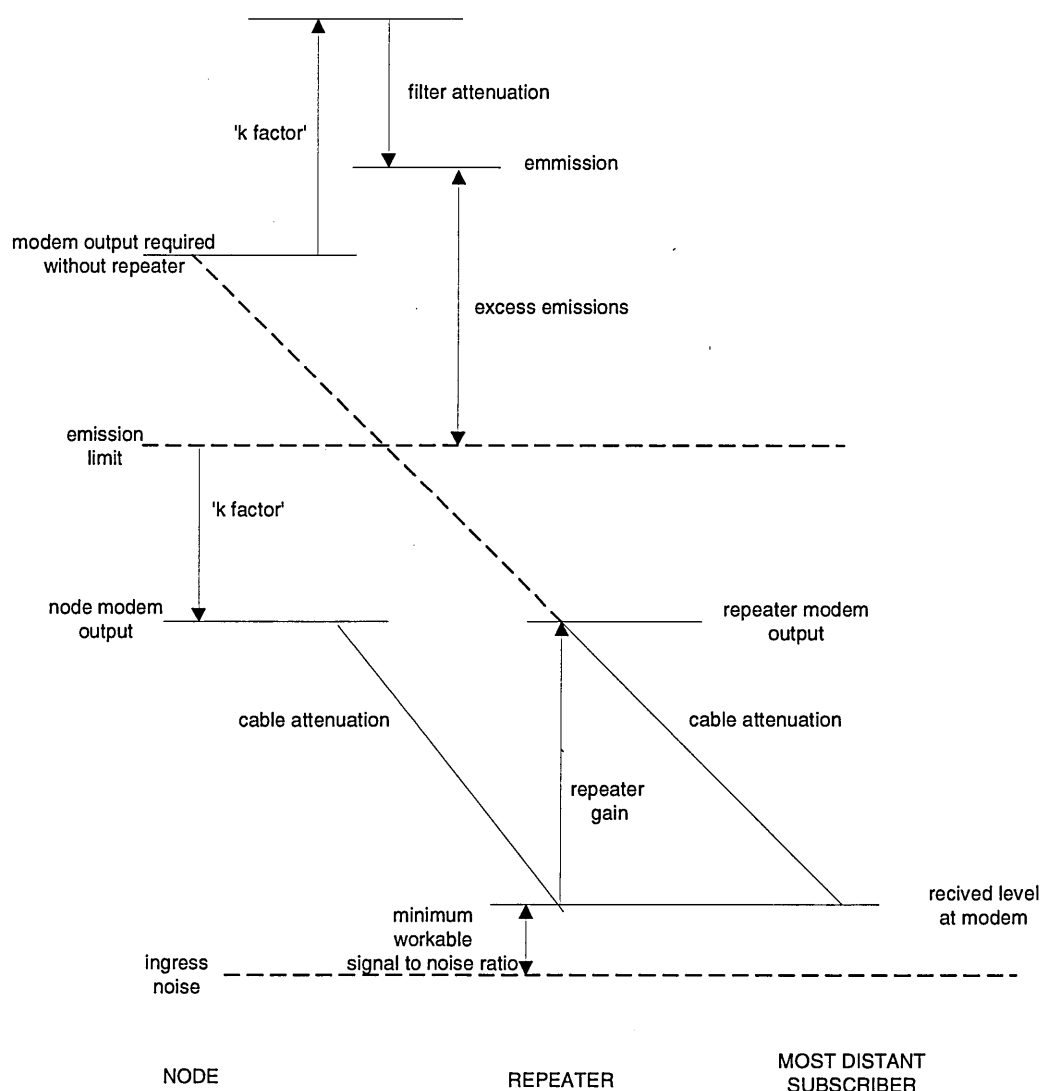


Figure 19 Downstream power budget with repeater

The power budget equations between the repeater and the node, between mid-hop repeaters and between a repeater and the most distant subscriber are the same as the upstream and downstream equations for an unrepeated hop [equations 3 & 4], each side of the repeater being treated separately.

In examining the effect of a repeater on the network performance it must be noted that each repeater will halve the data throughput as compared with the data rate on each hop because it cannot receive and transmit simultaneously in the same frequency band due to its transmitter blocking its own receiver. The mains wiring to which the repeater is attached is continuous past the repeater so that the two sides of the repeater are not isolated from each other. There are two alternative methods of operating a repeater, which are compared below:

- **Frequency translation:** in this mode the input and output sides of the repeater operate on different frequencies. If the data rate is to be maintained the signal bandwidth on each side will be the same and therefore half of the available spectrum will have to be used on the node side of the repeater and the other half used on the subscriber side.

- **Store and forward:** the same frequencies can be used on each side of the repeater if the retransmission is delayed until the entire message has been received. This means that each message from the node to the subscriber takes twice as long to transmit as it would on one hop, thus reducing the data rate [section 9.4.2].

6.2. Ingress Noise Models

This section provides details of two ingress noise models developed to assist with the assessment of the noise resulting from the reception of radio broadcasts by the cabling of the distribution network and the buildings connected to it.

6.2.1. Ingress noise at a node

The ingress noise at the node will affect the upstream direction of transmission. Fig 20 depicts a PLT system with n houses connected to one feeder. Each house is assumed to inject the same amount of ingress noise power (P_h Watts). This is reduced by the attenuation of the feeder between the house and the node. The distance between houses is assumed to be constant and each inter-house section of feeder has an attenuation of x dB.

These assumptions are likely to be correct for estates of similar houses.

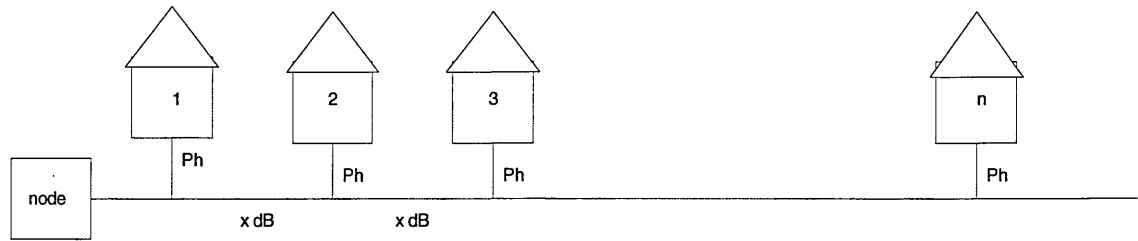


Figure 20: Ingress noise at a node

Although shown in fig 20 in dB, as it would be measured, the model requires the attenuation to be expressed as a ratio. This conversion is achieved using equation 5:

Equation 5: Conversion of attenuation figure from dB to ratio

$$as = 10^{x/10}$$

The ingress noise power at the node (P_n) is then given by equation 6:

Equation 6: Ingress noise power at a node

$$P_n = \sum_{x=1}^n \frac{P_h}{as^x}$$

Where P_n (W) is the total noise power at the node, P_h (W) is the noise power injected by a house, as is the attenuation ratio and x is the number of houses.

Equation 6 may be expressed to a form convenient for use in an Excel spreadsheet, as shown in equation 7:

Equation 7 Ingress noise power equation usable in a spreadsheet

$$P_n = \frac{Ph \times (1 - as^{-n})}{(as - 1)}$$

A study was made using Excel to investigate the trend of the ingress noise at a node for feeders with varying numbers of houses and cable attenuations. It was found that the noise did not increase significantly with more houses beyond a point that depended upon the attenuation of the cable. The results are shown in table 6. The calculations from which the table is derived used the following parameters:

- 20m distance between houses
- -64.3dBm noise power per house ($P_h = 3.98 \times 10^{-7} \text{ W}$)

The noise power is derived from the measurement of ingress noise at a house in the 7MHz to 10MHz band [section 8.2.7] and the 51dB/100m loss is an average for the underground cables measured [table 37].

Table 6: Ingress Noise Limits at a node

Cable loss per 100m (dB)	Number of houses at which limit occurs	Ingress noise power at node (dBm)
30	12	-68.74372
51	6	-73.76409

The ingress noise on the feeder remains the same for more houses than is shown in the table for an accuracy of three decimal places.

Substations have more than one outgoing feeder and the node connected to the substation busbars will receive the noise from all the connected feeders. Although the noise sources are the same for all feeders the signals will be de-correlated by the different phase shifts. The total noise power will therefore be given by the addition of the noise power from each feeder, so that the total noise power is represented by equation 8.

Equation 8: Total ingress noise at a node

$$Pn(total) = nf_1 + nf_2 +nf_n$$

Where nf_1 to nf_n are the noise powers on the feeders 1 to n.

This calculation was made for cases with from two to six feeders with from one to ten houses per feeder. This showed similar limiting characteristics to the single feeder case. Using an ingress noise level of -73.76409dBm per feeder (derived from table 6) and three feeders, the limit occurred at six houses per feeder with a level of -70.7538dBm. This is slightly greater than the level of -72dBm measured at The Lawns in the frequency band 7MHz to 10MHz [section 8.2.7].

The architecture of a PLT system is similar to that of a CATV system, and the ingress noise in both types of system is due to pickup of radio broadcasts on the distribution plant and the house wiring. A model for

ingress noise in CATV systems has been produced by Bell Communications Research [Carangi, Chen, Kerpez, & Valenti, 1995]. Their model is empirical and was obtained by graphing the average noise level against the number of subscribers and finding the equation of the best-fit curve. Their equation is shown as equation 9.

Equation 9: CATV ingress noise model

$$y = a \log(n) - b$$

where y is the noise level, a is network dependent, b depends upon the channel number in use and n is the number of subscribers.

Because of the differences between PLT and CATV networks a direct quantitative correlation is not expected, but it is useful to compare the trend of the ingress noise for two multi-drop systems. Using the CATV model with the same injection per house as the proposed PLT model showed significantly different performance; the CATV model showed a steep increase in ingress noise to 100 houses and did not level off below 240 houses. However, it should be noted that CATV systems use low-loss cable and contain reverse-path amplifiers which could not be used in PLT systems. Some of the noise in a CATV model is thermal noise contributed by these amplifiers and the attenuation of ingress noise is low.

As it stands this PLT model applies only to systems without incoming filters but it can be made to apply to filtered systems by reducing the parameter P_h by the filter attenuation.

6.2.2. Ingress Noise at a Subscriber Modem

Noise on the downstream path will represent a limit to the performance of a PLT system, because that is the direction in which the maximum bandwidth is normally required. Therefore, it is important to be able to predict the noise at a subscriber modem. The proposed model is an extension of the model for the noise at a node and the same assumptions are used. The situation at a subscriber modem is shown in fig 21

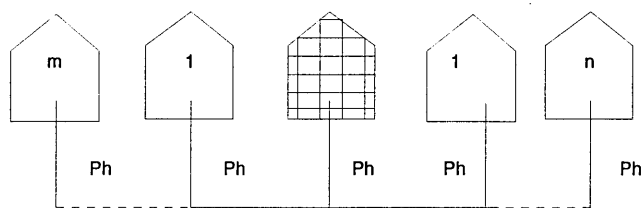


Figure 21: Ingress noise at a subscriber modem

Referring the calculations to the house marked with a pattern in fig 21, the noise power for the left hand side is given by equation 10:

Equation 10: Subscriber ingress noise left side

$$P_n = \sum_{x=1}^m \frac{P_h}{as^x}$$

And for the right hand side, the noise power is given by equation 11:

Equation 11: Subscriber ingress noise right side

$$P_n = \sum_{x=1}^n \frac{P_h}{as^x}$$

The total noise power is given by RSS addition of the powers from the left and right sides and the noise received by the wiring of the service point itself:

Equation 12: Total ingress noise power at a subscriber modem

$$p_{n(total)} = \sum_{x=1}^m \frac{P_h}{as^x} + \sum_{x=1}^n \frac{P_h}{as^x} + P_h$$

As has been seen from the example of the PLT node, the network noise is typically at or below the level injected by a house. This means that the level at a subscriber modem will be dominated by the ingress noise received on the local house wiring. However, this will be reduced by the attenuation of any incoming filter and the calculation can be adjusted for the filtered case by reducing the local P_h by the filter attenuation or using the network noise, whichever is the greater.

6.3. Calculation of Channel Capacity

Having obtained figures for bandwidth and signal to noise ratio, it is possible to calculate the capacity of the channel in terms of the maximum number of bits per second that it can support without a significant probability of error. The calculation is performed using equation 13:

Equation 13: Calculation of system capacity

$$C = W \times \log_2(1 + SNR)$$

Where C is the capacity in bits per second, W is the bandwidth in Hz and SNR is the received signal to noise ratio (expressed as an arithmetic ratio, not in dB).

Equation 13 is derived from theorem 18 in Shannon's Bell Systems paper [Shannon 1948]:

"Theorem 18: The capacity of a channel of bandwidth W perturbed by an arbitrary noise source is bounded by the inequalities shown in equation 14.

Equation 14: Shannon noise power inequalities

$$W \cdot \log_2\left(\frac{P + N_i}{N_i}\right) \leq C \leq W \cdot \log_2\left(\frac{P + N}{N_i}\right)$$

where P = average received power, N = average noise power and N_i = entropy noise power".

Equation 13 is therefore derived by assuming that the entropy noise power is effectively the same as the

average noise power, as is the case for white noise. As the received power, P , increases, the upper and lower bounds converge, thus making it possible to state an equation for the system capacity.

The use of Shannon's equation to calculate the system capacity in a noise environment resulting from the reception of broadcast signals may be questioned, because the theorem is based on the idea of the noise being Gaussian. Broadcast signals will be far less random than white noise and thus the calculated capacities may not match reality. As stated by Shannon, *"The operation of modulation is not [invariant under all time translations] since the carrier phase gives it a certain time structure"* [ibid]. In practice, white noise interference is the worst case, because *"For a given average power N , white noise has the maximum possible entropy"* [ibid]. In order to achieve greater accuracy it would be necessary to know the entropy of the ingress noise, which is not possible because of the multiplicity of modulation types, content and utilisation of frequencies in the HF band. However, it is this very diversity of use that means that the entropy of the noise is higher than for a simple single transmission and for this study the noise levels measured are averaged over 3MHz bands, thus maximizing the noise entropy for the calculations used in this thesis.

6.4. A method of Comparing the Performance of PLT Systems

The concept of 'Emission Factor' (EF) of a PLT system is proposed, to enable the efficacy of different modulation systems to be compared. Ideally, this would be done by trying different types of equipment on the same network, but that is impractical. The EF is a 'normalised' figure that will allow the emissions for a particular type of system to be averaged across all the networks measured that use that technology, while taking account of basic and measurable differences between the networks. The concept is illustrated in fig 22.

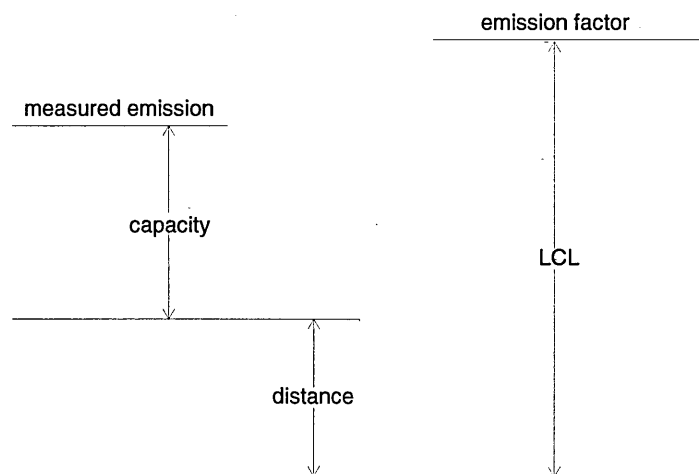


Figure 22 The emission factor concept

In the calculation, the distance used is the maximum unrepeatable distance served by the source under consideration. Rather than mixing logarithmic and linear

quantities, it would seem best to express distance and capacity in logarithmic terms (dB), so that the calculation of EF is as given by equation 15:

Equation 15: Calculation of emission factor

$$EF = \text{measured_emission}[\text{dB}\mu\text{V/m}] - 10 \times \log(\text{capacity}[\text{kbps}]) - 10 \times \log(\text{distance}[\text{km}]) + \text{LCL}$$

The principle is that the measured emission is adjusted downwards for systems that support a higher data rate or that are communicating over longer distances, as both of these factors should increase the power required. But if emissions are caused by network unbalance higher LCLs should reduce the emissions, so the EF is increased by the network LCL, because higher LCLs should result in lower emissions. The units of EF are $(\text{dB}\mu\text{V/m})/\text{km}/\text{kbps}$.

It should be noted that it may be necessary to include another factor to account for the number of buildings fed by a network, because each building will:

- Increase the ingress noise by acting as a receiving antenna
- Increase the attenuation experienced by the PLT signal by acting as a transmitting antenna and radiating some of the PLT signal away from the network.

Because the number of buildings on the networks on which measurements were made was not recorded, it has not been possible for the contribution of buildings to be factored into the current EF model. Probable influencing factors are:

- The number of buildings connected to the network
- The physical volume of the buildings (and hence the 'capture area' of their wiring systems)
- The topology of the wiring in the buildings (ring circuits or tree and branch for power distribution)

It is impractical to calculate the EF over the entire HF band; therefore when calculating the EF, the emissions and LCL will be averaged over the arbitrary 3MHz sub-bands used in this study for other assessments of PLT systems.

6.4.1. Example of EF for Systems Already Tested

The principle of EF is that the factors shown in figure 22 will all theoretically influence the actual emission of a PLT system. However, the exact form of the EF equation can only be determined empirically, given enough results from field measurements. For example, LCL may not be a useful indicator of the emission properties of a PLT system [section 3.2]. A calculation of EF has been made for three Ascom systems and a Main.net system, as an example of how the EF concept is intended to work [PSCRG

2004]. The results are shown in table 7, which is based on data from the measurement programme carried out on trial PLT systems in Scotland and at Littlewick Green.

Table 7: Illustration of Emission Factor

measurement point	system	sub-band (MHz)	LCL (dB)	distance (km)	capacity (kbps)	measured emission (dBuV/m)	emission factor (dBuV/m)	notes
Elgin master	Ascom	1 - 4	21.2	0.15	570	33.15	35	1. Capacity per carrier as stated by Ascom 2. Distances scaled from plan 3. Distance to furthest repeater used
		4 - 7	15.8	0.15	570	38.86	35	
		7 - 10	12	0.15	570	50.94	44	
Lotland Road slave (cleansing depot)	Ascom	1 - 4	39.5	0.021	570	31.1	60	1. Capacity per carrier as stated by Ascom 2. Distances as stated on plan
		4 - 7	41.8	0.021	570	20.02	51	
		7 - 10	36.4	0.021	570	22.55	48	
Woolley Hall	Ascom	1 - 4	only one carrier in use					1. Capacity as stated by Ascom 2. Distance to master
		4 - 7						
		7 - 10	24.9	0.05	570	60.55	71	
Woolley Hall	Main.net	1 - 4	39.8	0.05	173.5	35.6	66	1. Capacity reading from control software, based on file transferred 2. Distance to master measured
		4 - 7	28.5	0.05	173.5	40.46	60	
		7 - 10	24.9	0.05	173.5	48.43	64	

It was expected that a given type of equipment would have the same emission factor regardless of the network on which it operated, but that assumption is not supported by table 7. However, the following points should be noted:

1. The actual data capacity achieved by the Ascom systems is not known, the figures used being based on the manufacturer's data sheets.
2. The Elgin system is known to be 'clean', having a low number of service connections and thus probably lower attenuation and impulse noise than the other systems.

-
3. The Lotland Road location was an industrial site with a large quantity of heavy electrical plant.
 4. The installation at Woolley Hall (Littlewick Green) was a temporary setup provided at short notice for the use of the research group and was not representative of a commercial deployment of the systems.
 5. There is some doubt about the efficacy of LCL as a predictor of PLT emission performance where the emission measured is from the wiring of a building [section 3.2]
 6. PLT operators may set their equipment above the minimum power level required for adequate communications [section 8.1.4].

6.4.2. Use of Emission Factor

For theoretical studies, the use of EF will facilitate the comparison of systems deployed in the field with the capacity predications. Given enough measurements with complete data sets, it may become possible to make a statistical analysis to provide a calculation of EF, with confidence limits, for each type of equipment available for test. Then, by knowing the proposed feed distance and by measurement of its LCL, it will be possible to predict the emissions of a PLT network before it is implemented

6.5. Intermodulation

A potential form of interference resulting from the operation of PLT systems is the generation of additional signals as a result of mixing in non-linear elements of the power distribution system, such as diodes formed by poor connections or elements of power supplies in appliances. This section provides details of the problem, which is potentially significant for the band planning for PLT systems. It will be shown how intermodulation products might affect radio services on frequencies not intentionally present in the PLT spectra, or possibly cause problems to the PLT service itself.

6.5.1. The Intermodulation problem

The problem of assessing interference from PLT systems is complicated by the presence of other RF signals on the mains. Such signals are present due to reception of broadcast radio services by the mains wiring in the street or in buildings, or by coupling from other metallic media such as CATV circuits, ADSL circuits and computer network wiring. When a number of signals are present it is possible for additional signals to be formed by mixing in non-linear devices connected to the power network. Such devices may be passive; eg diodes

formed by corroded connections, or active, such a switch-mode power units.

The additional signals formed are known in radio engineering practice as intermodulation products (IMPs). They are of concern to operators of multi-user radio sites as IMPs of significant magnitude may fall on the frequencies of receivers on the site, disrupting the reception of the weaker wanted signals. It has been known for IMPs formed by passive mixing on a radio site to be re-radiated with sufficient magnitude to cause interference to reception at some distance from the site, although fortunately this is a rare occurrence.

6.5.2. Characteristics of Intermodulation Products

IMPs are formed by various combinations of the signals present on the network. Because of the number of calculations required, the best way of predicting the spurious signals that could be produced is to use an IMP predication program. For this study the program 'IM' version 1.1 was used, which was obtained as a free download from the Berne Institute of Technology, Switzerland. To illustrate the type of calculations performed to predict intermodulation products, an example of some of the possible mechanisms in the simple case of two interacting signals f_1 and f_2 is shown below:

$$2f_1 - f_2$$

$$2f_2 - f_1$$

$$3f_1 - 2f_2$$

$$3f_2 - 2f_1$$

$$3f_2 - f_1$$

$$3f_1 - f_2$$

A run of a commercial intermodulation product calculator (IM) was made using typical PLT carrier frequencies. The constituents of the run were as follows:

- Three ETSI access band frequencies
 - 2.4MHz
 - 4.8MHz
 - 8.4MHz
- Three ETSI indoor frequencies
 - 12.8MHz
 - 18.2MHz
 - 22.4MHz
- A local radio station frequency.
 - 1.17MHz

The run found a total of 3475 IMPs of between second and fifth order, of which 2020 were in the 1.6MHz to 30MHz band. The program used predicted the relative amplitude of the IMPs as well as their frequencies, and the relative levels for the various orders of IMP predicted is shown in table 8.

Table 8: Amplitude of predicted IMPs using typical PLT frequencies

signals	Relative amplitude (dB)
Wanted	+10
2 nd order IMPs	-10
3 rd order IMPs	-15
4 th order IMPs	-8 to -13
5 th order IMPs	+5 to +12

As can be seen from the table, the highest levels are associated with the fifth order intermodulation products. The amplitude of IMPs does not have a direct relationship with the amplitude of the signals from which they are formed. In fact, the level of an IMP in dB is related to the order of the process that causes it, so that a second order process results in a 2dB rise in level when the constituent signals are raised by 1dB, and for a third-order process the IMP rises 3dB for each 1dB increase of the input. Fitting an attenuator at the input of a receiver or spectrum analyser therefore provides a simple test of whether the signal under examination is genuine or an IMP within the equipment.

It should be noted that processes of up to ninth order can provide significant IMPs capable of affecting services, depending on the wanted signal levels involved.

6.5.3. Potential Effects of IMPs on a PLT System

To predict the potential effect of intermodulation in the distribution mains on a real PLT system, a further run was made using the intermodulation product prediction program, IM. The run used the Ascom access band frequencies, 2.4MHz (C1), 4.8MHz (C2) and 8.4MHz (C3) as inputs, assuming a level of 10dBm per carrier. The result of the prediction is shown in fig 23.

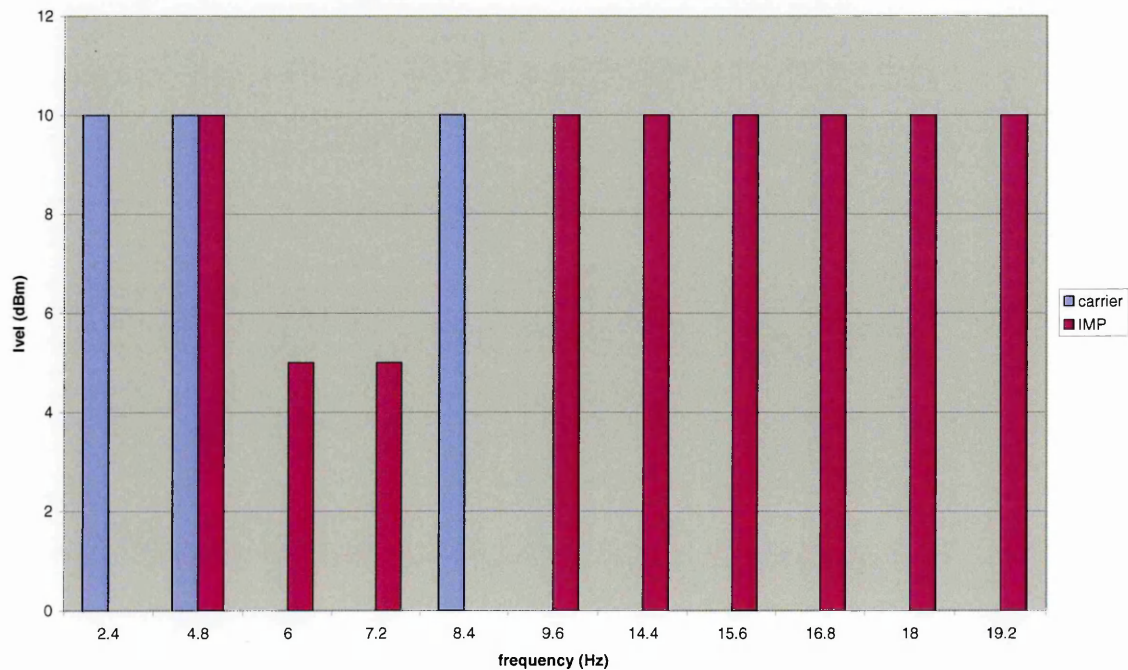


Figure 23: Potential Ascom intermodulation products

The derivation of the IMPs shown in fig 23 is as shown in table 9. Some IMPs may be generated by more than one

interaction, as shown in the two columns of the table;
which of the mechanisms produces an observed IMP
depending on the network conditions.

Table 9 Derivation of IMPs shown in fig 23.

frequency	mechanism 1	mechanism 2
4.8	$4 \cdot C1 - C2$	
6	$2 \cdot C1 + 2 \cdot C2 - C3$	$C2 - 3 \cdot C1 + C3$
7.2	$2 \cdot C3 - 2 \cdot C1 - C2$	
9.6	$2 \cdot C3 - 3 \cdot C1$	$3 \cdot C2 - 2 \cdot C1$
14.4	$4 \cdot C1 + C2$	
15.6	$3 \cdot C3 - 2 \cdot C2$	
16.8	$3 \cdot C1 - 2 \cdot C2$	$4 \cdot C2 - C1$
18	$3 \cdot C3 - C1 - C2$	$4 \cdot C1 + C3$
19.2	$2 \cdot C1 + 3 \cdot C2$	

It should be noted that although 4.8MHz is one of the three carrier frequencies (C2) it is also formed as a result of a fifth-order intermodulation effect between itself and the 2.4MHz carrier (C1). This has the potential for blocking the 4.8MHz carrier or at least reducing its signal to noise ratio, thus reducing the data capacity of the access system. As the Ascom modulation spread around the carrier frequencies is quite wide, there is also the potential for the IMP at 19.2MHz to affect the in-house carrier at 19.8MHz, if the house uses an in-house system together with an access system running via carriers 1 & 2. This is not believed to be a

likely condition, but could cause problems that would be difficult to diagnose in a working system. According to information obtained from Scottish and Southern Energy, the access modem is always placed at the incoming supply position; acting as a gateway translating the access band signals to in-house carriers between the supply termination and the position of use, so that the situation could occur, given the wrong choice of frequencies. A further potential result of intermodulation is to fill in deliberate gaps in the frequency spectrum of a PLT modem, such as 'notches' to protect the amateur bands. This concern is supported by BBC Research [Stott & Slater 2003, pp 23]

6.6. Modulation and Coding Systems

The practical realisation of the capacity of a PLT system depends upon the correct choice of modulation system. This section discusses the characteristics of various digital modulation schemes and the criteria for selecting a scheme suitable for PLT systems.

6.6.1. General Principles

Most digital modulation schemes operate with an analogue carrier, which is varied in some way to represent the digital information to be transmitted². One of the simplest types of digital modulation is two-frequency

Frequency Shift Keying (FSK), in which one frequency is used to represent a binary 1 and another to represent a binary 0. One or other of the frequencies is always present on the line while communication is in progress. Another simple method is to use a single carrier frequency and to shift the phase of the carrier in one direction to represent a binary 1 in the input data stream and to shift it back to represent a binary 0. This is known as binary Phase Shift Keying (PSK). At the receiver, detection is achieved either by comparing the phase of the received carrier with a locally generated carrier (coherent detection) or by comparing the phase of the current cycle of the received waveform with that of the previous cycle (differential detection). Phase shift key systems using differential detection are referred to as differentially coherent Phase Shift Keying systems (DPSK) [Lahti 1989 pp234]. Coherent detection³ has a small advantage in error rate over differential detection at a given signal to noise ratio.

It is possible to achieve higher data rates at the same line symbol rate⁴ by increasing the number of states of the modulation. Thus, four-frequency FSK permits the sending of two data bits per line symbol, as does Quadrature Phase Shift Keying (QPSK). Higher levels of

² one exception is Ultra Wide Band (UWB), which uses narrow pulses

³ aka synchronous detection

⁴ aka 'baud rate'

complexity are possible by using combinations of amplitude and phase shift modulation; thus a system with eight amplitude levels at each of four phase shifts provides 32 distinct modulation states and is known as 32QAM⁵ and supports 5 bits of the input data stream per symbol of the line (five bits per baud).

While the use of higher level modulation schemes appears to offer higher data transmission rates within the same line bandwidth, Shannon's work shows that the gain is not 'free' and that bandwidth and signal to noise ratio are inexorably linked to data rate. Higher level modulation systems delivering more bits/Hz of line bandwidth require a higher signal to noise ratio if the same data rate is to be achieved with error-free performance within a lower bandwidth. Fig 24 shows the variation in signal to noise ratio required for error-free operation with systems varying from one bit/Hz (basic two-shift systems) to 8 bits/Hz (256 state systems such as 256QAM). The graph is derived from equations 16 and 17.

Equation 16: Relationship of required SNR to bits/Hz

$$\text{bits_per_Hz} = \log_2(\text{number_of_states})$$

Equation 17: Equation used to produce fig 24

$$\text{SNR} = 10 * \log_{10}(2^{\frac{C}{W}} - 1) \quad \text{where } C/W \text{ is the number of bits/Hz.}$$

⁵ 32 (state) Quadrature Amplitude Modulation

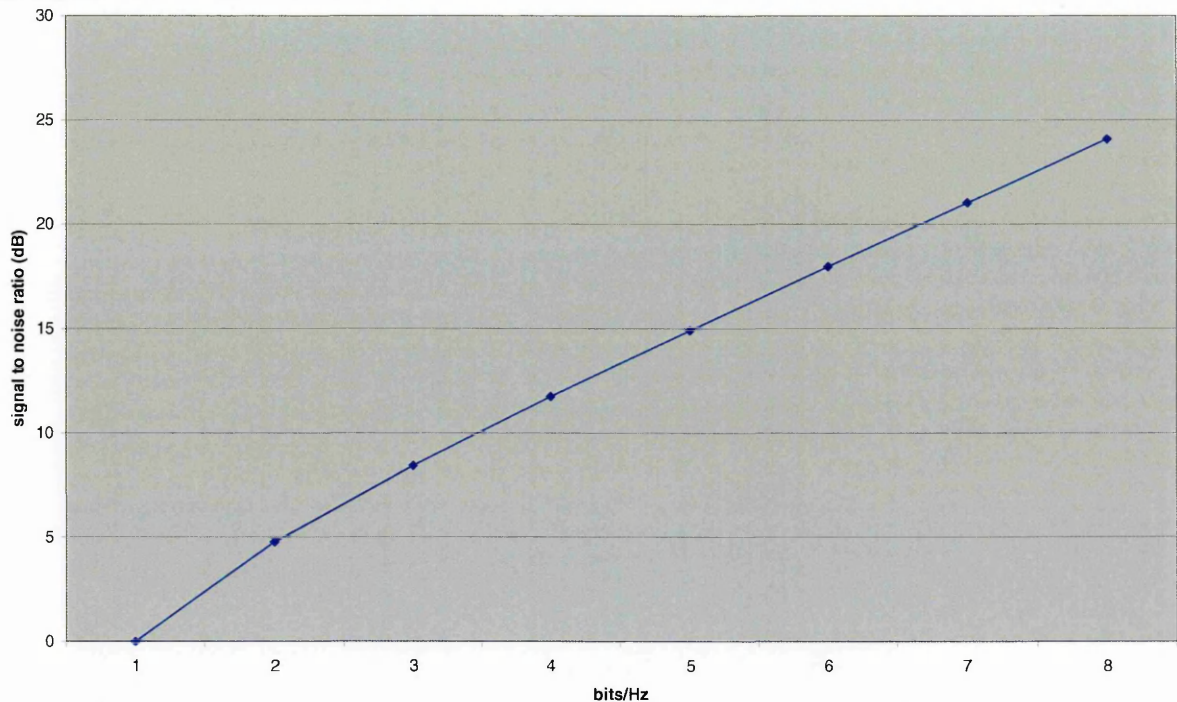


Figure 24: Variation of required signal to noise ratio with modulation efficiency

It can be seen that the simple two-level schemes such as two-frequency FSK can provide error-free performance at 0dB signal to noise ratio, while 256QAM would require 24dB of signal to noise ratio for error-free operation.

6.6.2. Transient Performance of Modulation Systems

In addition to the steady-state considerations of signal to noise ratio, the response of modulation systems to mains transients must be considered. The effect of a transient will be to prevent the reception of data for the duration of the transient event, and possibly for

slightly longer due to ringing caused by shock excitation of resonant circuits within the mains network or the modem itself. The number of bits affected by a transient depends upon the data rate and hence the symbol duration on the line, and the length of the transient.

With simple modulation schemes the faster the data rate the shorter is the bit duration, the relationship being given by equation 18

Equation 18: Relationship of bit duration to data rate

$$bit_duration = \frac{1}{data_rate}$$

Where the data rate is expressed in Mbps the equation provides the bit duration in microseconds. It can thus be seen that with a 1Mbps system using FSK modulation a 100µs transient will affect 100 bits of data, which cannot be recovered by any sensible error correction code. If higher level modulation schemes are used the data loss would be even greater; for example a 32QAM scheme operating at the same line rate would lose 500 bits of user data to the same transient event.

The need to provide protection against transient interference has led to the development of Orthogonal Frequency Division Modulation (OFDM), which is used extensively in PLT systems and digital terrestrial

broadcasting applications. OFDM works by splitting the line data stream over a large number of carriers; systems using more than 1000 carriers being common. The user data rate is thus divided by the number of carriers to provide the line data rate, so that a 1Mbps system using 1000 carrier OFDM would have a line rate of 1000 symbols per second and hence a symbol duration of 1000 μ s. The carriers are spaced 'orthogonally' (with their centre frequencies separated at the per carrier line data rate, eg at 1MHz intervals for a data rate of 1Mbps per carrier). This prevents interference between the sidebands of the individual carriers. A further reduction of line rate is available by using high-level modulation of the carriers, so that, for example, a 1Mbps system using 1000 carrier OFDM with 32QAM modulation of the carriers would have a line symbol duration of 5000 μ s. This is sufficient to avoid interference by most of the transients encountered on a LV distribution system [section 8.2.8]. Fig 25 shows the relationship between transient duration and number of bits affected for a number of different modulation schemes.

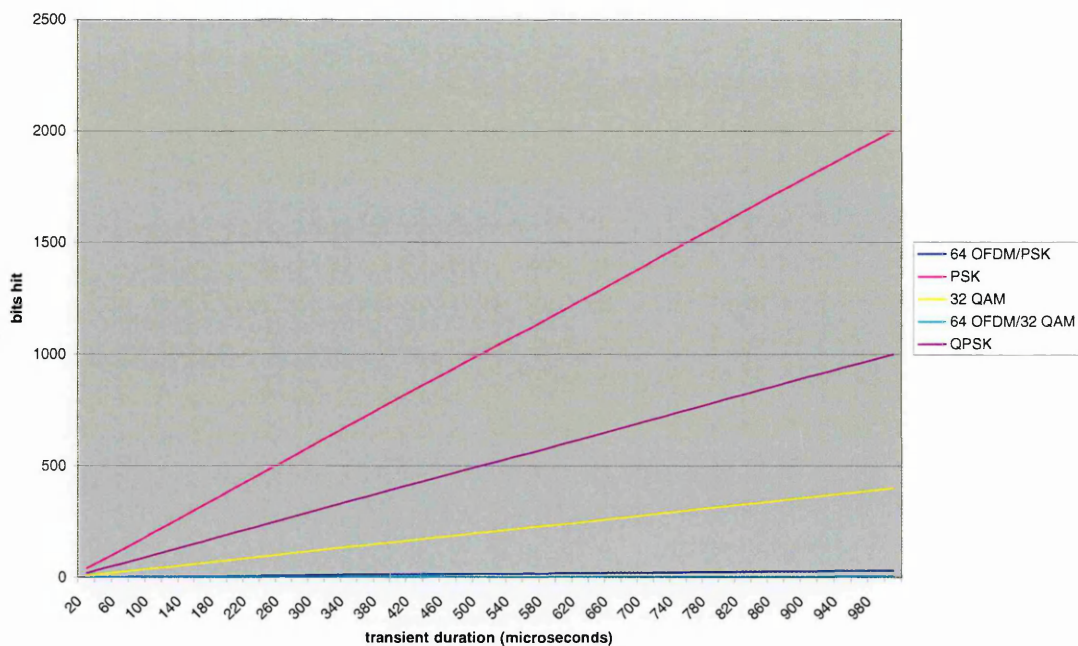


Figure 25: Relationship between transient duration and bits affected for various modulation schemes

The graph shows the performance of various modulation schemes at a user data rate of 2Mbps for transients of up to 1000 μ s, which covers the commonly encountered transient events. It can be seen that, of the modulation types examined, 64 carrier OFDM with 32QAM carrier modulation offers the best performance; it is not obvious from the graph but a 1000 μ s transient will only result in the loss of six bits, which can be corrected by a suitable Forward Error Control (FEC) line coding system. However, some manufacturers use many more carriers, providing protection against longer transients without the need for FEC. It is believed that it is easier to implement OFDM in a DSP based modem than it is to develop a complex FEC system; the OFDM implementation requiring a

standard Inverse Fast Fourier Transform (IFFT) algorithm [Oberg 2001 pp259]. In addition to having advantages in dealing with transient interference, OFDM has "...advantageous properties for transmission on channels with multipath transmission..." [ibid pp260]. This is an advantage in the PLT situation, where multi-path signals may occur due to reflections from service terminations and branch mains.

Of course, as previously considered, the use of higher level modulation of each carrier requires higher signal to noise ratios and this must be considered in the design of an OFDM system. However, the loss of one carrier due to a high ingress noise level will have a limited effect on the overall data rate, which may not be noticed by a user. OFDM therefore offers advantages against both ingress noise and transient interference. In the case of interference complaints it is also possible to switch off individual carriers to prevent the interference (a process described as 'notching') which is attractive to some PLT operators, although it may not be effective in practice [section 6.5.3].

Another type of multi-carrier scheme that is used for ADSL services is known as Discrete Multi Tone (DMT). While this has similar characteristics to OFDM it is distinguished from it by the fact that, unlike OFDM, it

does not use a common modulation system for each carrier [Abe 2000 pp68]. Instead, DMT "...enhances the OFDM model by allowing variable spectral efficiency among the sub bands....some sub bands can use more aggressive modulation schemes than other sub bands" [ibid]. This is understood to mean that the level of modulation scheme is selected to provide the best possible data capacity within the noise environment applicable to that carrier. It is known that some PLT systems do use different modulation levels depending upon the noise environment [conversation between author and Mitsubishi engineer in Quaenbeyan, November 2004].

6.6.3. Interference Properties of Modulation Systems

Although the choice of modulation systems is critical to the performance of the PLT system, it is also necessary to consider the impact of the radiated and conducted emissions from the system. Any problems arising from the operation of a PLT system will normally affect radio users and the perception of the problem depends upon the amount of energy reaching the affected receiver. A convenient way of examining the impact of different modulation schemes is thus to compare the Power Spectral Density of the modulation (PSD).

PSD is defined in Watts/Hz and can be calculated as shown in equations 19 or 20, depending on the units required.

Equation 19: Calculation of power spectral density

$$PSD[W / Hz] = \frac{signal_power[W]}{bandwidth[Hz]}$$

or in logarithmic units as

Equation 20: Calculation of power spectral density in logarithmic terms

$$PSD[dBm / Hz] = signal_power[dBm] - 10 \times \log(bandwidth[Hz])$$

Using equation 20 it is easy to convert from PSD into signal power in a given receiver bandwidth, facilitating signal to noise calculations if the wanted receive signal level and bandwidth are known.

It is clear that the lower the PSD the less interference power will appear in a user's radio channel, which should reduce the perceived effect of the PLT system emissions. For this reason, modulation schemes that reduce the PSD must also be considered. One such scheme is Direct Sequence Spread Spectrum (DS-SS), which is also known as 'pseudonoise' [Cooper & McGillem 1988 pp269].

A direct sequence transmitter uses a pseudo-random code generator and binary adder to increase the data rate of the input data stream before applying the result to a conventional modulator; typically a PSK modulator. This provides a number of 0/1 transitions (referred to as

~~'chips')~~ for each bit of the input data stream and results in an output signal with characteristics approaching those of white noise, depending upon the PN generator characteristics. At the receiver an identical PN generator is used to de-spread the signal, so that the data stream can be demodulated⁶. The effect of the process is to increase the bandwidth of the signal compared to conventional modulation schemes and Shannon's equation shows that the same error rate can be achieved with a lower signal to noise ratio, thus allowing the transmission power to be reduced. Spreading the signal power in this way means that the PSD of a DS-SS signal is lower than that of a discrete carrier system for the same performance. It should be noted that frequency hopping spread spectrum does not provide the same advantages; although the carrier will only be present on any given frequency in the hop pattern for a short time, while it is there the level will be the same as for a system without frequency hopping and may thus cause disturbance to radio reception as a tone at the hopping frequency.

Reception of a DS-SS signal is only possible by a receiver that uses a PN generator capable of producing an identical code to that used at the transmitter. This allows system users to occupy the same spectrum in the

⁶ the transmitting and receiving PN generators must be accurately synchronized

same area by using different codes. This is referred to as Code Division Multiple Access (CDMA).

The properties of multi-carrier modulation systems such as OFDM and the advantages of DS-SS have led researchers to investigate the combination of the two techniques [Fazel & Kaiser 2003 pp41]. Two systems are proposed; Multi-Carrier Direct Sequence Code Division Multiple Access (MC-DS-CDMA) and OFDM-CDMA. Because in MC-DS-CDMA the spectrum of the carriers is being increased it is only workable with a small number of carriers, each of which can be considered as a DS-SS system with reduced input data rate. Unfortunately, it is unlikely that there would be sufficient bandwidth available for that technique to be of use in PLT systems and it will probably be limited to use on the Extra High Frequency (EHF) radio bands above 1GHz.

6.6.4. Automatic Transmitter Power Control

A facility that is sometimes used on microwave links and mobile radio systems is Automatic Transmitter Power Control (ATPC). In radio systems the aim is to use the minimum transmission power necessary to maintain link integrity under the prevailing propagation conditions. In this way interference is minimised, especially in interference limited environments, such as cellular mobile radio networks. The control of the transmitter power is

a function of the bit error rate, the power being increased as the error rate increases due to a reduction in signal to noise ratio caused by an increase in path attenuation. Although changes in the network attenuation are negligible for HF PLT systems, the ingress noise does vary over the diurnal cycle and therefore ATPC could offer some advantages. There seem to be two opposed possibilities for employing ATPC in a PLT system:

- to maintain system performance: the PLT modem would be set to the minimum power required to maintain the performance of the hop during the day and ATPC would be used to increase the modem power output when the ingress noise increased at night
- to ensure minimum interference to radio services: the PLT modem would train by listening to the ingress noise and control its power output on frequencies with high ingress to avoid creating interference - this assumes reciprocity between ingress and emissions

A further use of ATPC is to adjust the subscriber modem power automatically depending on its distance from the node, but this is only a variation of the method of minimizing radio interference described above.

Either of the above methods of operation would help to minimize the radio interference potential of the PLT system. Measurements carried out on PLT systems [section 8.1.4] have shown that they tend to be installed with the modems set at or above the power output required to maintain communications under worst-case ingress noise conditions, so that the emissions from the system are excessive for much of the time.

The BBC have stated that to avoid interference to broadcast services PLT modems will have to be capable of monitoring their operating spectrum and notching their power injection dynamically, depending upon the prevailing propagation conditions [Stott 2004 p13]. This can be considered to be an extreme form of the use of ATPC for interference reduction.

6.7. Error Correction

In section 6.6.2 it was shown that the use of multi-carrier modulation schemes such as OFDM can provide protection against errors caused by transients. However, OFDM does not offer the lowest power spectral density, which is more readily achieved with DS-SS modulation. As DS-SS does not have OFDM's inherent protection against transient induced errors it is necessary to use suitable line encoding to provide the necessary performance from a

DS-SS system. The technique used is known as Forward Error Correction (FEC). In order to appreciate how this would be used, it is necessary to understand the basic elements of a digital communications system, which are shown in fig 26, in which the modulators and amplifiers are omitted for clarity and assumed to be combined into the 'communications system', which also includes the transmission medium.

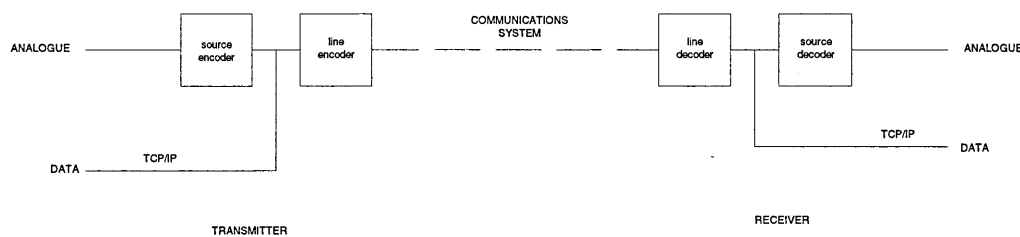


Figure 26: Elements of a digital communications system

For analogue inputs, such as a telephone interface, a source encoder is needed to convert the analogue speech signals to digital format. For a PLT system, this will digitise the analogue signals and pack the data into Internet Protocol format, Voice over IP (VoIP). Data signals originating from a computer, which may include VoIP, do not need to pass through the source encoder. The digital signals could be used to modulate the PLT carrier signal directly, as it is tempting to assume that the error correction inherent in TCP/IP is sufficient to ensure the accurate delivery of the data. However, TCP/IP error correction is an end to end process between source and user, using retransmission of errored packets.

This means that relying on it in this application would result in poor data rates, due to the long latency of the multi-hop routes and the high probability of transient errors. When experiencing data loss "...IP assumes congestion is the cause of packet loss and invokes congestion control mechanisms at the source" [Patel et al 2001]. Thus it is necessary in a PLT system to provide error correction on each hop forming the route, to "...hide the unwanted characteristics of the [PLT] links from the upper layers" [ibid]. That is the function of the line encoder and decoder, which provide error control over the hop by further encoding the TCP/IP data.

Hamming describes the use of block codes for error detection and correction [Hamming 1950]. The number of bits corrupted by a transient event can be calculated using equation 21:

Equation 21: Number of bits corrupted by a transient event

$$b = \frac{t}{T}$$

where b = the number of bits affected, t is the transient duration in μs and T is the bit duration in μs .

The minimum distance required for error correction is the number of bits that must change between valid codewords. It is calculated as shown in equation 22 [Lathi 1989, pp675].

Equation 22: minimum distance of error-correcting code

$$\text{minimum distance} = 2t + 1$$

where: t is the maximum number of errors that can be corrected by the code. This means that to correct two errors requires a minimum distance of 5 between code words. This can be achieved with a 15,8 code [ibid, table 9.1, pp276]. This code has a total word length of 15 bits (n), of which 8 are message bits (k) and 7 are check bits ($n-k$). The efficiency of the code (also known as the code rate) is given by equation 23.

Equation 23: efficiency of error-correcting code

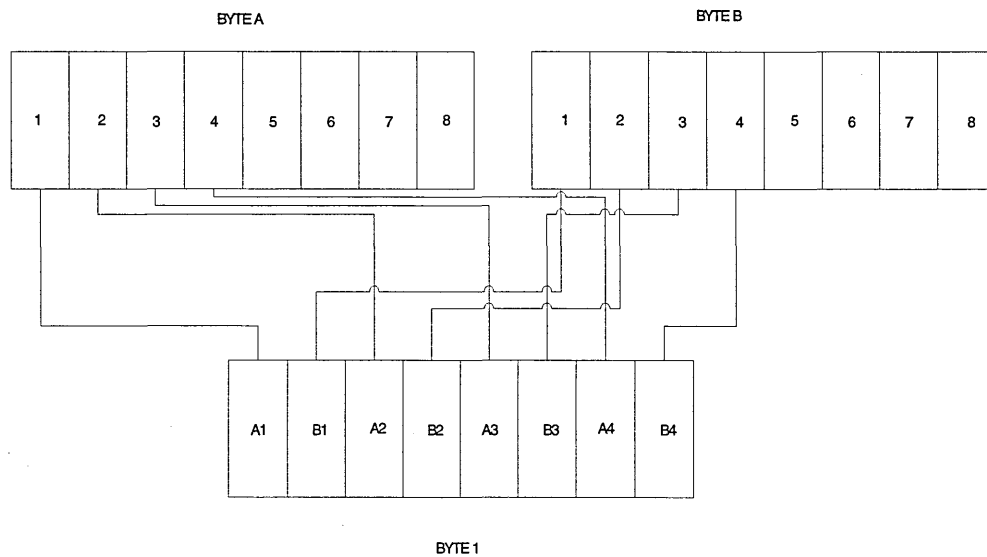
$$e = \frac{k}{n}$$

which gives a value of 0.533 for the 15,8 code that is capable of correcting two errors per word. This means that the data throughput of such a code will be 53.3% of the line transmission rate.

Given a typical transient duration of 100 μ s, even at a modest line rate of 1Mbps a transient will affect 100 bits, so that this code would not prevent loss of data, despite the reduced data throughput of 533kbps.

Fortunately, there is way to improve the performance of error correcting codes without further reducing the data throughput, by using bit interleaving [Oberg 2001 p195].

This was used by Vodafone in its CDLC modems for the TACS analogue cellular networks in the 1980's. The process is shown in outline in fig 27. Blocks A and B are the data blocks, which have been encoded using an error correcting block code. Block 1 is then formed as shown with the first four bits of blocks A and B. The rest of block 1 is filled similarly from other blocks in the data stream. Block 1 is then transmitted to line. This process is repeated for all the message blocks. It can be seen that if the whole of block 1 is lost during the transmission process, a suitable error correcting code can restore the lost data. Extension of the idea to suit the characteristics of the transmission medium can provide a significant reduction in transient errors without having too much effect on the data throughput. It should be noted that, in practice, the bit interleaving process would be carried out over a larger number of bytes than shown here; the diagram having been simplified for clarity.



6

Figure 27: Bit interleaving

The combination of error correcting codes with bit interleaving is therefore a practical alternative to OFDM for protection against transient induced errors, and could be combined with OFDM if the required error protection cannot be achieved by that means alone.

6.8. Summary

This chapter has shown how standard telecommunications design procedures can be adapted for the design of PLT systems. It has introduced the concept of intermodulation and shown how intermodulation products have the potential for interfering with the transmission of the PLT signals or producing radio interference. The choice of modulation and coding systems to deal with

transient interference has also been discussed and the advantages of multi-carrier systems, such as OFDM, have been shown. The use of coding on each PLT hop to combat transient interference has been examined and the disadvantages of relying on TCP/IP for error correction have been explained.

The next chapter provides details of the techniques used for the measurements undertaken for this research programme, which were based on the requirements of the models described in this chapter.

7. MEASUREMENT TECHNIQUES

It can be seen from section 6.1 that the following parameters must be known in order to determine the potential performance of a PLT system:

- cable attenuation
- k factor of buildings and the LV distribution network
- ingress noise
- the variations of these parameters with time.

In addition, information is required on the transient interference [section 6.1.2] and the intermodulation products [section 6.5] present on LV distribution systems.

The basic parameters that determine the potential performance of a PLT system can only be quantified by measurement on LV networks that do not carry a working PLT system. In addition to these 'clean network' measurements, it has been necessary to carry out measurements on trial PLT systems to determine the extent of potential radio interference, which is the major concern of standardisation groups and radio users. Conducted measurements are also required on PLT trial systems, to facilitate the examination of the relevance

of conducted standards and their efficacy at protecting radio services.

This chapter describes the methods used for the various types of measurement undertaken in support of the research programme. Because the measurements were carried out on different sites and with different teams, some variations of method occurred. The evolution of the techniques with experience, the effect of these variations on the accuracy of the measurements and general issues of measurement uncertainty are also discussed.

7.1. Attenuation and Impedance

The attenuation tests were automated by the use of a HP8753D network analyser. The test connections used are shown in fig 28.

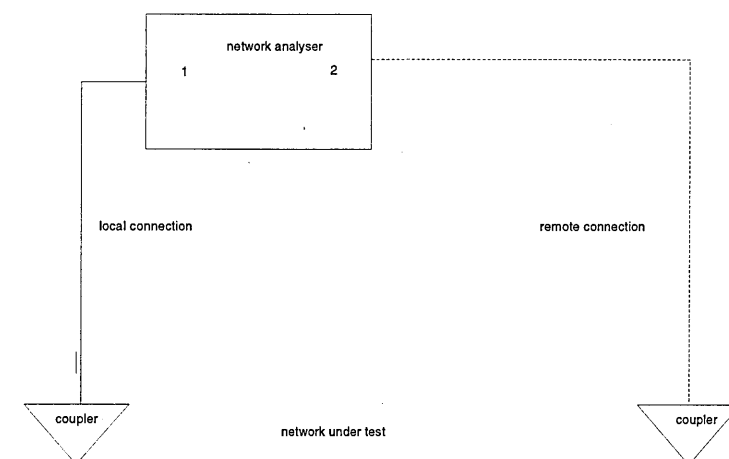


Figure 28: Use of network analyser

The network analyser was installed at the house or substation and port 1 was connected to the network via the local coupler. A low-loss coaxial cable was run around the streets to the coupler at the remote measurement point by tucking it into the gutters of the road and using rubber road crossing strips as required. The cable from the remote coupler was connected to port 2 of the analyser, thus facilitating measurements through the required part of the network.

The output power of the analyser was set to 10dBm (10mW). Measurements were made at 50kHz intervals in the required bands 1-11MHz and 10-20MHz. The results were output to floppy disk in HP CITIfile⁷ format as a tab and comma delimited text file, which could be imported to Microsoft Excel for processing. The following parameters were recorded automatically for each frequency step:

- S21 port to port forward gain
- S12 port to port backward gain
- S11 port 1 return loss
- S22 port 2 return loss

Each measurement is represented by as a pair of values corresponding to the real and imaginary elements. These

were processed using Excel spreadsheets. The format of the results allowed the calculation for each frequency step of the transfer function, including phase shift between ports, and also facilitated the calculation of the port impedance, expressed in terms of the loss and angular phase shift between the ports.

7.1.1. Test Access Connections

The measurements required access to the LV conductors at the house, in the link boxes and in the LV distribution pillar at the substation. The couplers used for making connections for the tests provided the following features:

- Safety of the operators
- Safety of the test equipment
- A power supply for the test equipment
- Wideband signal transmission between the LV system and the test gear

7.1.1.1. Operator safety

The low voltage system has a fault level of 25MVA at the substation busbars [Tew 2005]. Therefore, at the substation the prospective short-circuit current is of

⁷ Common Instrumentation Transfer and Interface file format

the order of 35kA [ibid] and care is essential. Operator safety was ensured by the following precautions:

- Connections to the LV network at the substation busbars and in link boxes were made using approved test leads with integral BS1362 5A fuses, terminated in crocodile clips.
- Connections at the house were made via 10A metering fuses in panel mounted fuse carriers.
- To comply with the Distribution safety rules, all work in substation pillars and link boxes was carried out by a certified *Competent Person*, ".....recognised by the Electricity Company as having sufficient technical knowledge and/or experience to enable him to avoid danger....." [ENA 2005, sec D.21 pp 20].

7.1.1.2. Test Equipment Power Supplies

In order to power the test equipment in the substation and at the link box it was necessary to provide a direct connection to the LV conductors. The couplers therefore incorporated two 13A sockets and a mains filter to prevent noise from the test equipment power supplies and mains leads being injected into the signal input. Because the filters incorporated capacitors in parallel with the mains a decoupling inductor was also included

between the filter and the mains input. Couplers used in the house did not have the test equipment power takeoff connected, the test equipment being operated from the building wiring. It was also found possible to power equipment in the substations from a 13A socket in the pillar, so the power takeoff facility was only used for measuring ingress noise at the link boxes.

The power supply provision within the coupler introduced a safety hazard requiring care in operation. It was found that before the cable from the remote coupler was attached to the test gear, the screen of the cable was at a potential of about 125VAC to earth, as measured with meter of 10k Ω /Volt sensitivity. This voltage could deliver an uncomfortable shock while attaching the cable to the earthed port of the network analyser. The hazard was present because of the decoupling capacitors in the filter used to power the test gear and led to the modification of the couplers used remotely by disconnecting the test gear power supply and filter, which was not required at the remote access point.

7.1.1.3. Signal Transmission and Test Equipment Port Protection

The arrangement of the signal coupler used is shown in fig 29. This coupler can be used for reception or transmission of signals.

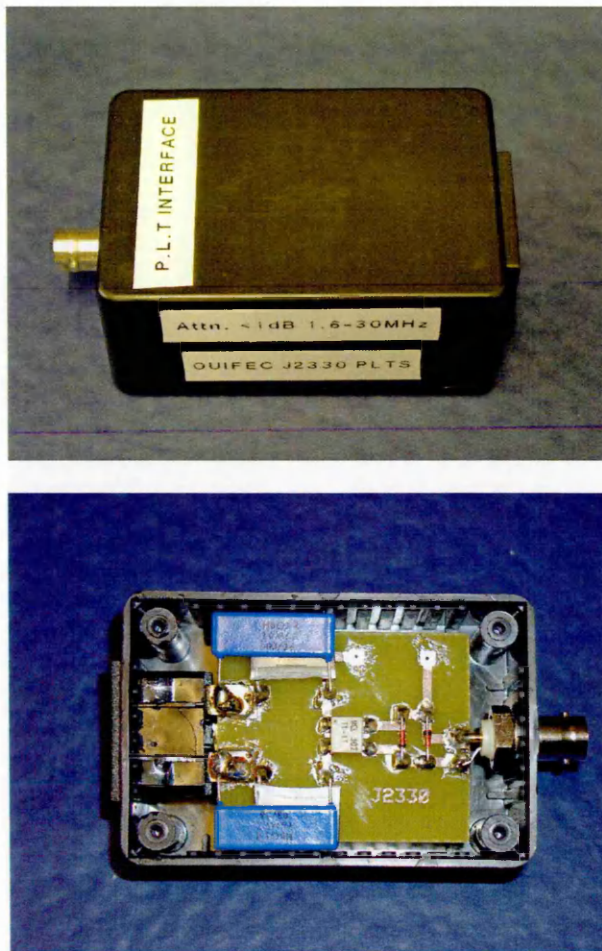


Figure 30: OU LV coupler outside (top) and inside (bottom)

The PSCRG version of the coupler uses the same circuit, component values and printed circuit board layout as the metal box version shown in use in the substation picture. Therefore, the performance of the two units should be similar. The PSCRG couplers were calibrated before use by connecting a pair back to back (by linking their mains ports) and performing a frequency run using a signal generator and the measuring receiver. In this test setup the maximum loss across the frequency range 1.6MHz to 30MHz was found to be 1dB per coupler. The actual losses were as shown in table 10 and were used as a transducer

factor, so that the loss was compensated in the measurement file from the receiver.

Table 10 Transducer factors for PSCRG conducted measurements

Frequency (MHz)	Attenuation (dB)
1.6	0.75
2.2	0.5
5.0	0.4
12.0	0.4
16.5	0.5
30	1.0

The measurement error associated with this procedure is related to the unknown source impedance of the mains and the 50 Ω impedance of the test equipment. A first estimate of the possible measurement uncertainty was made using the Bull model for mains impedance [Bull J H, 1975] as the source impedance and calculating the error. The Bull model is only valid to 10MHz and calculation shows that the mean error is approximately -6dB. A further estimate of the possible error has been made by using some measurements of mains impedance detailed in section 7.1.2, and is shown in fig 31.

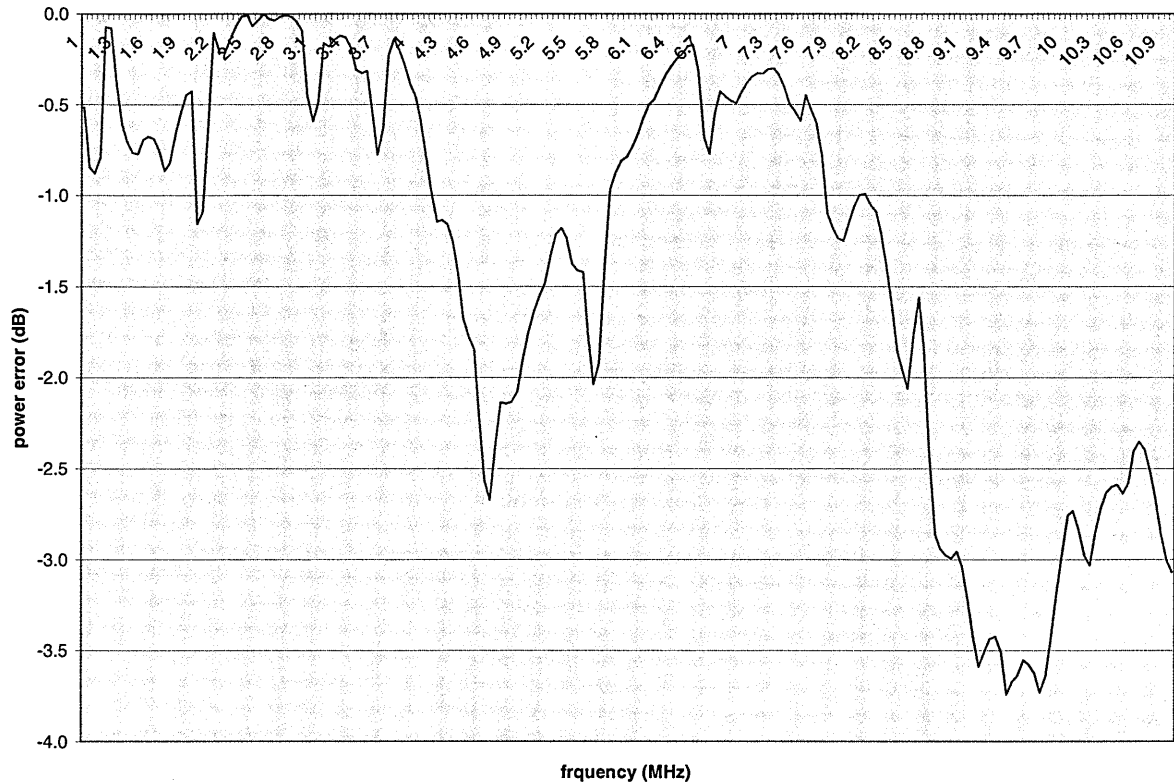


Figure 31: Power error resulting from mismatch of test equipment

The graph shows the power error, which can be seen to be a maximum of 3.7dB with the range of impedances used for this assessment, which were derived from actual impedance measurements taken at the author's house. The error could be avoided by using a high impedance wideband buffer amplifier with unity gain between the LV coupler and the measuring instrument.

The coupler is bi-directional and was used for signal injection for k factor measurements as well as measurement of voltages on the mains system. The same errors are applicable when the coupler is used for signal injection. The errors were eliminated for the transfer

function measurements by calibrating the network analyser with its test cables and the couplers connected back to back.

7.1.2. Impedance

The data files generated by the network analyser for transfer function analysis also provide impedance values, which are of use in the design of PLT systems. Each S parameter is represented by a pair of values, consisting of the R & I (Real and Imaginary) parts of the measured value. The coefficients are presented in such a way that the equation 34 is true:

Equation 24: Use of S parameters

$$V_{out} = V_{in} \times S_{xy}$$

where V_{out} is the output voltage of the appropriate port in response to the stimulus V_{in} , and S_{xy} is the S parameter appropriate to the test being used.

To determine the network impedance, the parameters S_{11} and S_{22} were used; ie the reflection coefficients at the network input and output ports used for the test.

7.1.2.1. Calculation of the Network Impedance from the Analyser File Data

The impedance is calculated using S_{11} and S_{21} . The conversion to an impedance value is carried out as follows:

- Calculate the magnitude of the reflection coefficient, S_{xy} :

Equation 25: Derivation of reflection co-efficient from CITI file data

$$S_{xy} = \sqrt{(S_{real}^2 + S_{imag}^2)}$$

where S_{real} and S_{imag} are the real and imaginary parts.

- Calculate the network impedance ($Z_{network}$), based on the 50Ω input and output impedance of the analyser:

Equation 26: Calculation of impedance from reflection co-efficient

$$Z_{network} = 50 \times \frac{(1 + S_{xy})}{(1 - S_{xy})}$$

This was done for both S_{11} and S_{22} for each measurement taken. Details of the results obtained are given in appendix C.

7.1.3. Steady State Noise

Two methods of measurement of the steady state noise on a network have been used. Steady State noise tests were carried out at houses, substations and link boxes. For one method a spectrum analyser (HP 8560E) was connected to the main at the measurement point using a coupler. This method is shown in use at a substation in fig 32. Testing quickly revealed that in the frequency range used for broadband PLT the principal noise sources were radio stations, rather than noise generated by domestic electrical equipment. This conflicts with my experience of measurements in the Low Frequency PLT bands, where the major sources of steady state noise are TV timebase harmonics and universal (commutator) electric motors [Brannon,1995, pp59 - 62]. At my house, the measurements were carried out during the day and repeated after dark, to allow for differences in the ingress noise as a result of changes in ionospheric propagation.

The method using the spectrum analyser is tedious and inaccurate because the plots have to be analysed manually, leading to subjective errors of interpretation. The subsequent availability of a measuring receiver meant that the measurements could be automated by substituting the computer controlled receiver for the spectrum analyser and plotter. This allowed the value of ingress

noise to be determined in 5kHz steps across the 1.6MHz to 30MHz PLT spectrum and facilitated statistical analysis of the results by importing the file to Excel.



Figure 32: Ingress noise testing at The Lawns substation

In fig 32, the spectrum analyser is on the ground with the plotter on top. The doors of the LV pillar are open, showing two of the fuseways, each with three white fuse carriers fitted. The grey box on the ground in front of the pillar is the coupler unit, and one of the clip leads can be seen connected to the yellow phase (middle) busbar at a spare fuseway with no fuses fitted.

7.1.4. Transient Noise

Transient noise was measured at my house using a BMI Powervisa 100G Power Quality Monitor plugged into the house wiring. This instrument had an integral coupler, so that no external signal coupling equipment was required. It monitored the supply and recorded details of the type, duration and voltage of each transient onto a paper roll, with a time and date stamp to show when it occurred and a graphical interpretation of the event. The instrument is intended for checking supply quality and could only record transients that were large in terms of the expected PLT telecommunications signals. It records a number of other parameters of the supply in addition to transients, such as deviations from the frequency and voltage standards of the 50Hz supply.

A more sensitive test was also performed using a W&G type GM1 noise meter, which contains a steady state noise meter with a psophometric filter and a noise impulse meter that is not affected by the filter. The noise impulse meter could be set to count the number of noise impulses above a user-set level in a specified time period and recorded the number of impulses at the set level and 3dB above and below. Although this instrument is intended for making measurements on voice-frequency circuits the transient recorder is a wideband device and

the results should be valid for a system intended to work at HF. The meter was connected to the mains system using the LV coupler shown in fig 29 and the input impedance was set to $20k\Omega$ line bridging mode. Tests were of one hour duration and three level settings were used:

- -20dBm
- -30dBm
- -40dBm

7.1.5. Field Strength Measurements

Field strength measurements made for this programme comprise two types of measurement:

- Emission measurements
- K factor measurements

Emission measurements are made to determine the signal levels radiated from a working PLT system, while k factor measurements seek to quantify the transfer function between the injected power and the field strength (expressed in dB μ V/m) that it causes. The two types of measurement are basically similar, differing only in the source of the injected power. For the emission measurements, the PLT modems are the signal source, while k factor measurements are made using discrete unmodulated carriers applied from a signal generator.

7.1.5.1. *Emission Measurements*

Emission measurements are measurements of the electromagnetic field strength caused by the radiation of PLT signals by the network or building wiring (chapter 3). The measurement is carried out using a wideband HF antenna connected to a measuring receiver. The basic measuring setup has a noise floor of approximately 30dB μ V/m, which has been found to be adequate for measurement of PLT signals at a distance of 1m, as required by the MPT1570 standard. For the emission measurements, the measuring receiver is computer controlled, making measurements in 5kHz steps over the PLT frequency band 1.6MHz to 30MHz. When measuring it is important to ensure that the PLT system is active. The required activity is ensured by asking the system operator to arrange for a large file to be transferred in the appropriate direction for the duration of the test:

- Downstream for measurements at the node substation
- Upstream for measurements at a house with a subscriber modem.

This is done because the measuring receiver dwells on each frequency that is measured for a finite time; the sweep is not continuous. Most PLT systems use time division multiplexing (TDM) to separate the upstream and downstream transmissions, so that if the distant modem is

transmitting during the measurement period a low reading will be obtained, due to network attenuation.

The antenna was mounted on a tripod 1m above the ground. The receiver was battery powered to avoid using mains supplies that might have conducted PLT signals into the vicinity of the antenna, thus causing errors in the measurements. A photograph of a typical test in progress (Crieff) is shown in fig 33; this measurement is being made at a substation that contains a PLT node. The loop antenna on its tripod is visible, with the receiver on the ground and the battery pack that powers it supported on a cabinet above and beyond the receiver.



Figure 33: Emission measurement at a node

7.1.5.2. 'k factor' Measurement

The k factor measurement uses the same receiving setup as used for the emission measurements. It is made on networks that do not have a PLT system and is performed to assess the emission characteristics of a building, line or item of illuminated street furniture (lampposts, signs etc). The techniques used to make the measurements for this research programme have improved considerably as experience has been gained.

The author's initial measurements in Ipswich used a signal generator located at a fixed point on the network to provide the signal injection. Measurements were then made at points of interest by the Radiocommunications Agency mobile EMC test laboratory, which is shown in fig 34.



Figure 34 RA mobile EMC test laboratory outside house A

The measurements were made by taking the van as close as possible to the measurement point. This meant that measurements at houses were carried out at the full length of the driveways, a number of which were 13m long, as in the case shown in the picture. These measurements posed a number of problems, as follows:

- The fixed location of the signal generator meant that network attenuation affected the injection power to the structure under measurement.
- The long measurement distance meant that the signal strength was lower than could be achieved with the antenna at a distance of 1m from the building.

Both of these factors reduced the signal strength at the measurement position, so that problems with the noise floor of the equipment and the broadcast background noise meant that only a limited number of frequencies was suitable for measurement.

For the measurements, the signal generator was set to a clear frequency and the measurement taken, communications between the measurement point and the injection point being provided using two-way VHF portable radios.

Although it was possible to take the van much closer to the lamppost that was measured, the measurement distance established at the first house was used for consistency. Since the early measurements were carried out the process has been refined and limits have been proposed by the RA PLT Expert Group, so that the problems stated above have been resolved in later measurements by the following changes to the methodology:

- The signal generator is located within the building for which the k factor is to be measured, and connected via a convenient power socket close to the measurement point
- The signal level from the generator is increased from 0dBm to 10dBm or 20dBm by the use of a wideband amplifier, as required to bring the signal sufficiently above local and equipment noise floors to permit accurate measurement.
- The measurement is taken at a distance of 1m from the building
- To reduce the granularity of the measurements, the OUPSCRG is now experimenting with the use of a spectrum analyser and tracking generator for k factor measurement in order to obtain a better understanding of the frequency dependence of the k factor, although the results from this technique are not yet available.

Having obtained the measured values, the k factor is calculated as shown in equation 27, using the method proposed to CISPR [Wirth 2003].

Equation 27: Derivation of k factor [Wirth 2003]

$$k[\text{dB}\mu\text{V}/\text{m}-\text{dBm}] = E[\text{dB}\mu\text{V}/\text{m}] - P[\text{dBm}]$$

While the units of the k factor look odd when expressed in logarithmic terms, in fact they just mean that the emission of a structure is being expressed in terms of electric field in $\mu\text{V}/\text{m}$ per milliwatt injected.

The same equipment types were used for all the field strength measurements, as follows:

- Measuring receiver: Rhode and Schwartz ESH10
- Wideband HF antenna: Rhode and Schwartz HLA6120.
- The LV coupler [fig 29] to connect the signal source to the mains.

All k factor measurements used the 200Hz resolution bandwidth of the receiver, with which only the averaging detector can be used. The narrow bandwidth used was sufficient for the measurement of the un-modulated carrier from the signal generator and helped to eliminate broadcast interference. Although it also reduced the receiver noise floor, making the receiver more sensitive,

that was of no consequence because of the high noise floor of the wideband antenna.

7.1.6. Injection Voltage Measurements

Injection voltage measurements have been made on trial PLT networks. The measuring receiver was connected to the mains system via the coupler [fig 29] using either a convenient socket outlet, which is often available in a substation LV pillar as well as in a building, or using approved fused test leads where no socket is available or connection to a specific phase is required at a substation [fig 35]. As with the emission measurements it is necessary to ensure that the local modem is exercised for the duration of the test and this is done by downloading or uploading a file large enough for the test to be completed before the file transfer ends.

For measurements at a subscriber modem a 330mm mains lead was used to connect to a socket outlet adjacent to the modem. However, in one case that configuration caused the PLT system to fail. In that case, a standard 1m IEC lead was used.



Figure 35: Test connections in a fused end box at Boydd Ave substation, Crieff

The photograph shows the interior of a fused end box, which is a small pillar that is bolted to the transformer when only a small number of feeders is required, rather than using a free-standing LV pillar as shown in fig 32. Two of the white fuse carriers on each outgoing feeder are visible. The coupler is in the base of the box and the test clip fitted to the outgoing side of the yellow phase fuse can be seen.

7.1.7. Ingress Voltage measurements

The procedure for measuring ingress voltage is identical to the measurement of injection voltage, except that ingress voltage is measured with no PLT signals present on the system. It is subject to the same errors as injection voltage measurements.

7.1.8. Threshold Testing

There were three purposes for measuring the power injection and emissions from trial PLT systems:

- To determine the extent to which the system represented a threat to radio services
- To compare the emissions with the proposed limits
- For comparison with the capacity calculations.

When measuring emissions from a PLT system it was useful to know how close to the Shannon limit the system was working; ie how much power was being used in excess of the power required to maintain a link with an acceptable error rate. The system operator was therefore asked to carry out a test on a specified PLT hop - eg between the master and the first repeater - by running a test consisting of repeated TCP/IP 'pings' and reducing the power in steps until the error rate became unacceptable. The test was carried out twice - once during the day and

once after dark - to take account of diurnal variation in the ingress noise.

7.1.9. Intermodulation Testing

This section details the methods that can be used for intermodulation testing on mains networks. The procedure has been validated in the IFEC laboratory of the Open University at Walton Hall, but has not yet been carried out on distribution networks. With the interest in OFDM and notching to prevent radio interference, intermodulation testing is important because of the potential of IMPs to fill in the notches, thus reducing the efficacy of notching. Also, the effect of intermodulation on multi-carrier systems using large numbers of carriers might be to generate so many products that the result was more like wide-band noise than discrete carriers, leading to a general increase in the noise floor with consequent difficulties in the operation of the PLT system. The potential threat to discrete carrier systems has already been demonstrated [section 6.5.3].

7.1.9.1. Test Configurations

Because of the potential complexity of the IMPs if a modulated signal is used, it is preferable to use discrete frequencies for the initial tests. The use of

two signal generators facilitates complete control over the test and a number of test arrangements to meet different circumstances are shown in figs 36 to 38.

7.1.9.1.1. Testing a Network without PLT

The objective of IMP testing on mains networks is to establish the extent of the problem, to facilitate various aspects of system design. As there is less possibility of anomalous results when using unmodulated carriers, it is necessary to measure IMPs on networks that do not carry PLT signals. This section describes the method of making IMP tests on networks without PLT. The test setup is shown in fig 36. The combined output from the two signal generators (genA and genB) is connected to a 50Ω tee piece, which provides a connection point for the spectrum analyser. The hybrid has a dummy load to terminate the unused port. The use of the hybrid provides isolation to ensure that IMPs are not generated in the output circuits of the signal generators. Each signal generator should have a calibrated signal output level control but if not, a variable attenuator can be added between each signal generator and the hybrid.

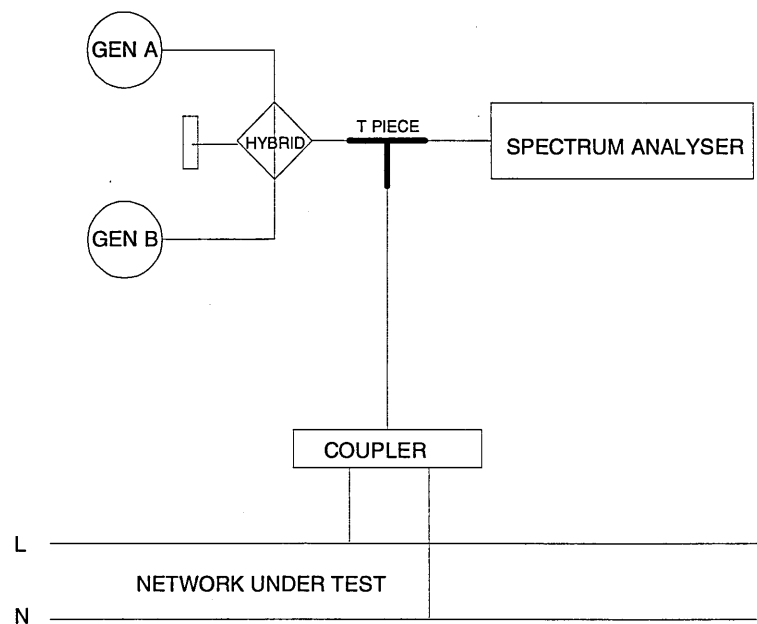


Figure 36: IMP testing of a network without PLT

7.1.9.1.2. Testing a Network with a PLT System

To test a network on which a PLT system is already operating, the arrangement of fig 37 can be used.

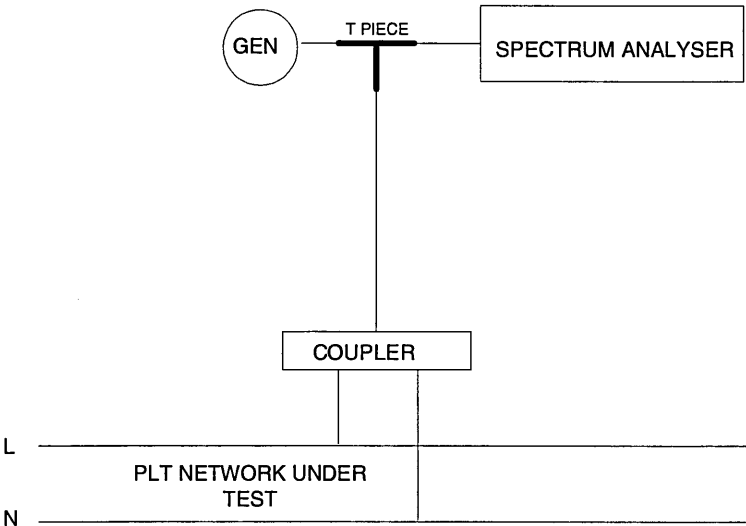


Figure 37 IMP testing of a network with PLT

In this case one signal generator is used to add a signal and the total spectrum is monitored using a spectrum analyser. The signal generator should have a calibrated signal output level control but if not, a variable attenuator can be added between the signal generator and the tee piece.

7.1.9.1.3. Testing an Appliance or PLT Modem

Having found IMPs on a system, it may be required to test a number of appliances connected to the system to determine which was responsible for the non-linearity that produced the spuri. This can be done using the arrangement shown in fig 38.

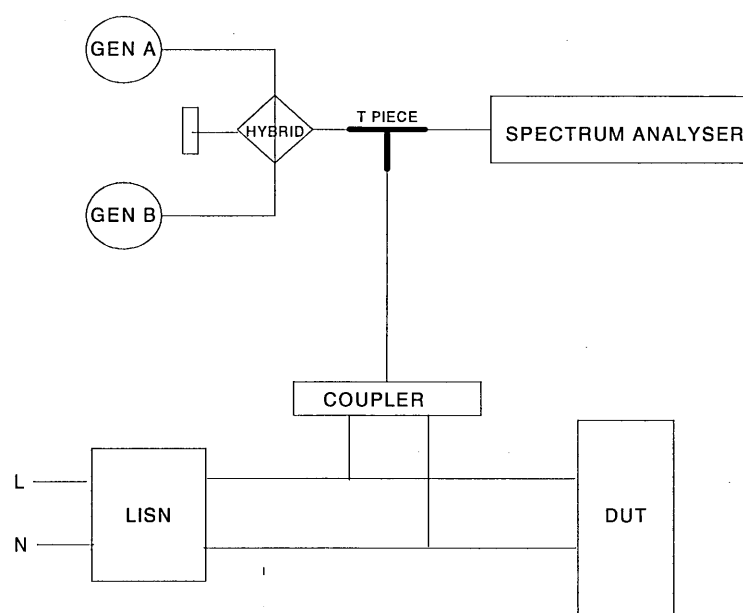


Figure 38 IMP testing of an appliance or a PLT modem

Again, a hybrid coupler is used to provide isolation between the two signal generators. A Line Impedance Stabilisation Network (LISN) is used to decouple the Device Under Test (DUT) from the LV network that powers it and to stabilize the mains impedance seen by the DUT.

It should be noted that while this arrangement seems attractive for the testing of PLT modems, in practice it is unlikely that they can be tested in isolation from their system, as they may not generate a carrier without communications from the system node.

7.1.9.1.4. IMP Emissions from Networks

For the purposes of testing the emissions of IMPs from a network, the arrangements shown in sections 7.1.9.1.1 or 7.1.9.1.2 should be used. In addition, it will be necessary to have an antenna system with a suitable low noise floor to permit the detection of the low-level IMPs.

7.1.9.2. Test Methods

The basic test method for all of the above types of test is as follows:

1. With no signal injection, determine the local spectrum and identify quiet frequencies. For network tests, also identify any strong signals present in the spectrum⁸ that may need to be taken into account in the formation of IMPs.
2. For PLT network tests, the frequencies of carriers transmitted by the PLT modems will form some of the frequencies used in the tests.
3. Identify test frequencies that have the potential to produce IMPs in quiet parts of the spectrum.
4. Set up the test equipment in accordance with the relevant diagram.
5. Set the signal generator(s) to the correct frequencies.
6. Increase the signal level on one generator while observing the effect on the calculated frequencies. Note the rate of rise in the level of the IMP relative to the rate of increase in the output level of the signal generator.
7. For tests of IMP emissions, first perform a conducted test and then look for emissions on the frequencies that have already proved to be present on the network.
8. Consider repeating conducted IMP tests on networks with the spectrum analyser connected via a separate coupler at a point distant from the signal generator injection point (far-end IMPs).

⁸ Eg broadcast signals from local radio stations

7.1.9.3. Validation of the Test Procedure

The IMP measurement methods described above were validated by tests conducted in the IFEC laboratory at Walton Hall. Details of the tests are given in appendix B. They confirm that the test equipment can detect intermodulation products on the mains system within the university.

7.2. Summary

This chapter has described the measurement techniques, the equipment used and the measurement uncertainty. The evolution of the measurement methods with increasing experience and availability of better test equipment has been explained. In the following chapter, the measurements made and the results obtained using these techniques are detailed.

8. MEASUREMENTS AND RESULTS

The measurement programme that provided the results used in this thesis was divided into two parts:

- Tests on trial PLT systems to determine the level of emissions from working equipment
- Tests on 'clean' LV distribution networks having no PLT equipment deployed on them, to provide quantitative information on the noise and attenuation of the networks and the emission characteristics of the connected buildings.

In this chapter, the results are grouped by the type of measurement (eg ingress noise), rather than by the site where the measurement was taken.

8.1. Measurements on PLT Trial Systems

Measurements have been made by the Open University Power Systems Research Group on a number of PLT trial systems in the UK, Europe and Australia. All of these systems were providing a real Internet connection service to paying customers. A comprehensive set of measurements was undertaken to establish the power injection levels and resulting emissions. These were compared with the

existing limit proposals discussed in chapter 4 of this thesis.

8.1.1. Conducted Measurements

A measurement of the modem injection voltage was made at each building or substation where an emission measurement was made. The results were plotted together with the various proposed limit lines discussed in chapter 4 of this thesis.

There are too many results to show the full set here, so a representative sample has been chosen to illustrate a number of points relating to modulation and equipment type.

8.1.1.1. Discrete Carrier Systems

A typical result for an Ascom system using GMSK modulation is shown in fig 39.

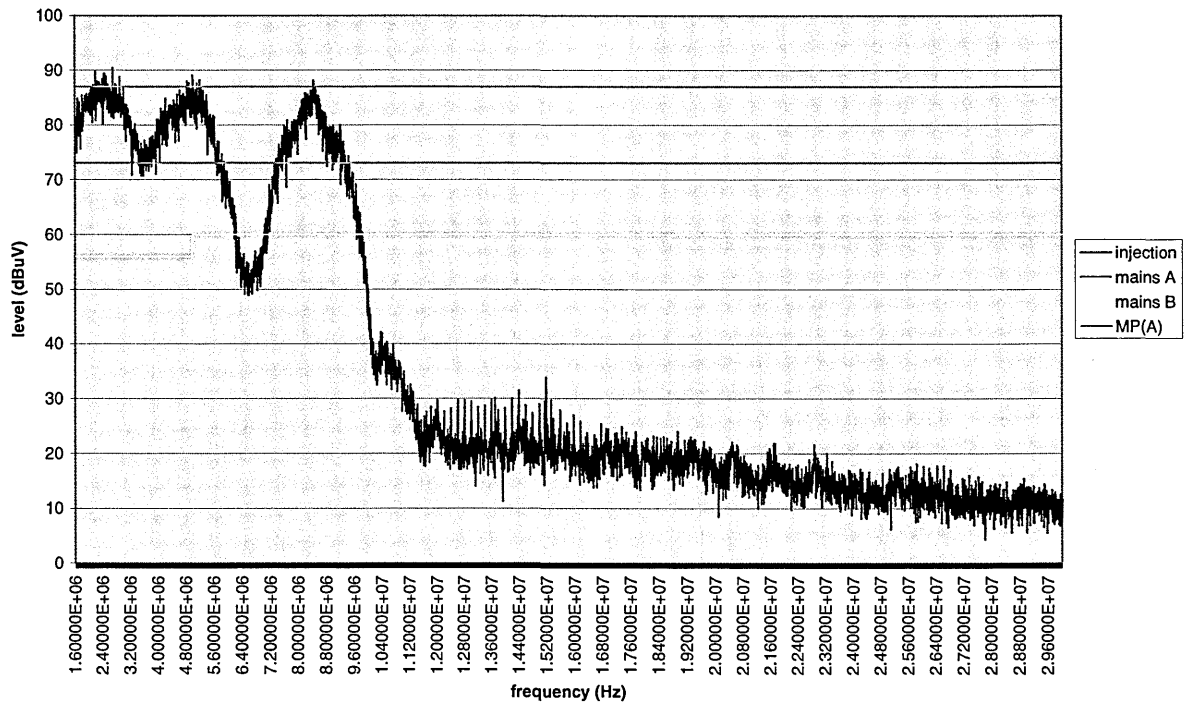


Figure 39: Modem injection voltage at Mycroft EAM

This measurement was made at a substation in Elgin that had a subscriber unit acting as the backhaul connection for a PLT network. The three carrier frequencies, 2.4MHz, 4.8MHz and 8.4MHz are clearly visible. The spikes that appear above the modulation envelope are broadcast stations that form the ingress noise; their level appears to be raised by the modulation envelope of the PLT signal. It can be seen that the amplitude of the lower two carriers exceeds all the proposed conducted limits, including the class A multipurpose port limit [section 4.2.2.2].

8.1.1.2. Spread Spectrum System

Fig 40 shows the injection voltage for a Main.net modem using Direct Sequence Spread Spectrum modulation. This measurement was made in Linz, Austria at a subscriber modem located in an apartment block. A large file was uploaded for the duration of the measurement.

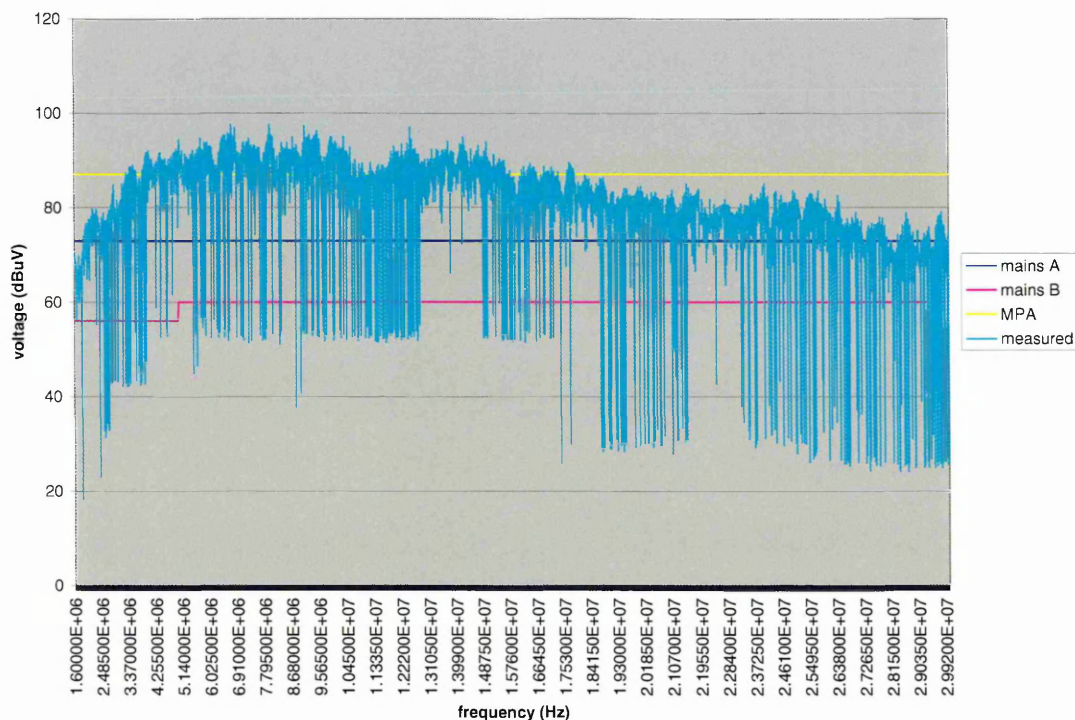


Figure 40 Main.net injection at Fichenstrabe 20, Linz

The spectrum of the PLT signal can be seen to fill the whole frequency band from 1.6MHz to 30MHz and is quite constant in amplitude; the spikes being caused by broadcast received as ingress noise. As with the AScom modem, the amplitude of the signal exceeds all the proposed limits, including the class A multipurpose port limit [section 4.2.2.2].

8.1.1.3. Orthogonal Frequency Division Modulation

An example of the output spectrum from an OFDM modem with 1024 carriers is shown in fig 41. This is a 45Mbps Mitsubishi modem using DS2 technology and the measurement was made in Quaenbeyan, a suburb of Canberra, Australia.

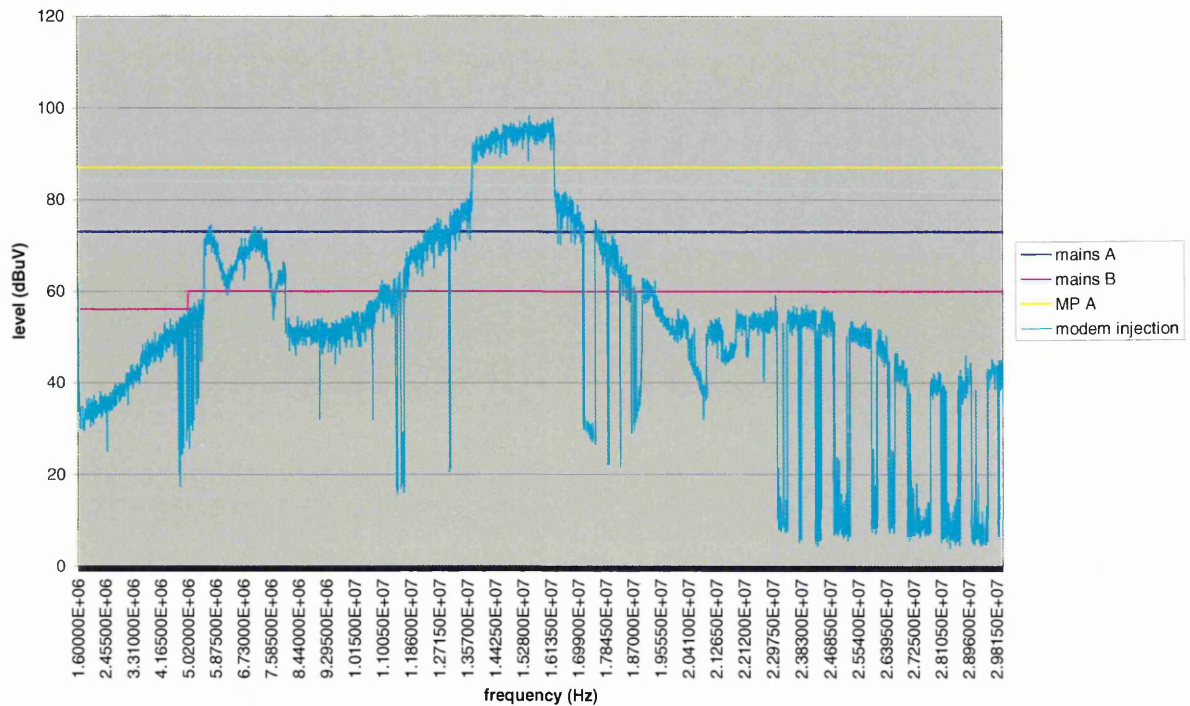


Figure 41: Modem injection at 33 Campbell St Quaenbeyan

Apart from using OFDM modulation, this system used a radically different band planning philosophy to the Ascom and Main.net units. The HF band is split into three sub-bands, each of which is further divided for upstream and downstream operation. It can be seen that there is a peak in its output between 13.8 and 16.3MHz, this portion of spectrum being designated as the link 2 upstream band, which was in use by the local subscriber modem. There is also a rise in level between 5.33MHz and 8.03MHz, which

is the link 3 downstream band. That is approximately 25dB below the local signal and is in use some distance away on the same network by a master station (node). The local modem signal exceeds even the class A multipurpose port proposal by approximately 15 dB.

8.1.1.4. In-house modem

The group only made one measurement on in-house PLT equipment, and that was carried out in the PLT laboratory at the University of Lille. The injected voltage is shown in fig 42.

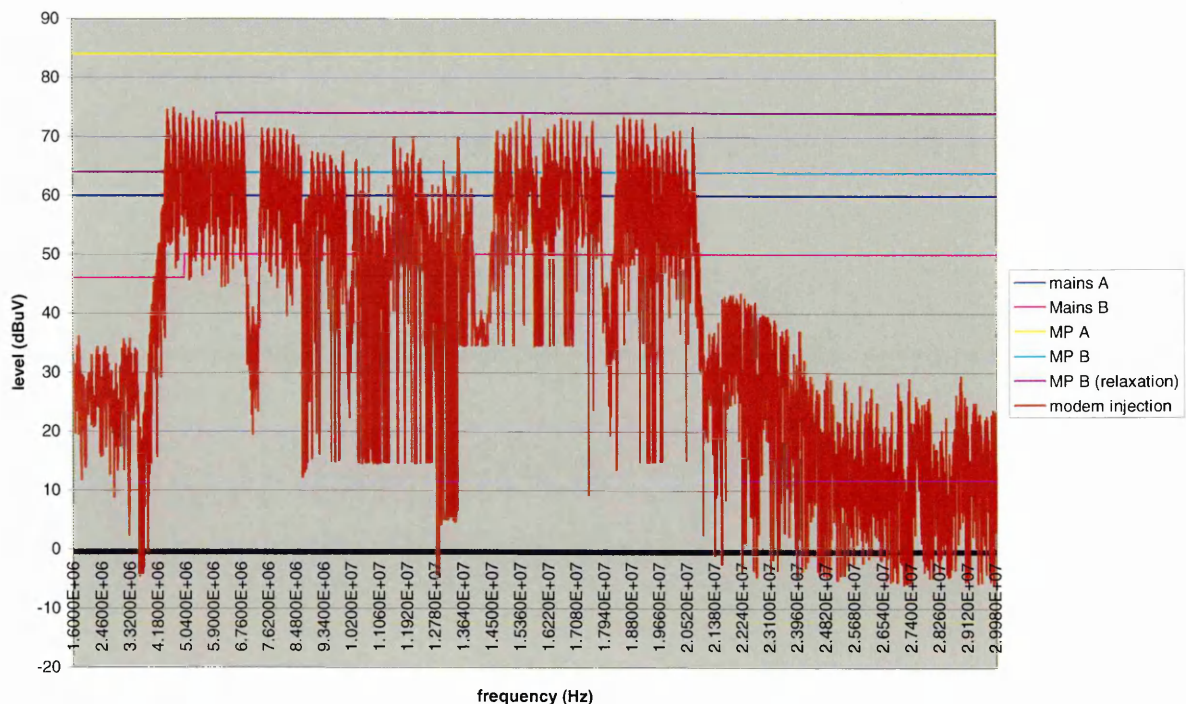


Figure 42 Injection voltage from Elcom EPLC 10Mi in-house modem

This Elcom EPLC 10Mi modem is intended for home LAN use. In the test, two modems were connected to socket outlets approximately 20m apart and a large file was transferred between them. The spectrum of the modem signal starts

from about 3MHz and thus encroaches on the Access band. Despite the short transmission distance the peak output exceeds the multi-purpose port class B limit and even exceeds the multi-purpose port class B relaxation [section 4.2.2.2] below 6MHz. It should be noted that the class B limits apply to this modem, because it is intended for in-house use.

8.1.1.5. *Comments on the Conducted Tests*

The above results have a number of similarities:

- All the spectra show that the modem signal injection voltage is in excess of the proposed limits, in most cases even the relaxation proposed to the CISPR 22 committee in I/89CD [section 4.2.2.2].
- None of the equipment adheres to the ETSI TS 101 867 proposal on access/in-house co-existence [section 4.2.2.1.1].

The results of the measurements on the in-house modem are particularly worrying because it has a level of about 75dB μ V in the 4.5MHz to 10MHz section of the access band. Considering the case of an access system, given a maximum injection (multi-purpose port A) of 87dB μ V and a typical loss in the 4.5MHz to 10MHz band of 42dB per 100m [table 27] (the lowest economic feed distance) the received signal at the most distant subscriber could be expected to be 45dB μ V or below, thus giving a wanted to unwanted

signal to noise ratio of -30dB. Using the same mains attenuation, this means that even at a house 100m from this in-house modem an access modem might only see a signal to noise ratio (wanted to unwanted signal strengths) of 0dB, apart from any considerations of ingress noise, which would worsen the available signal to noise ratio. As the house containing the in-house modem might not take the PLT access service there would be no incentive for the householder to fit an incoming filter and that relaxation of the co-existence rules would therefore not apply. This measurement thus shows clearly how an interference problem can occur that would be very difficult for a distribution network operator to resolve, especially given the 'ring fencing' between customer records (retail operations) and distribution operations introduced at privatisation of the UK electricity industry. It is a clear demonstration of the importance of standards and proper product testing to ensure compliance.

8.1.2. Emission Measurements

Emission measurements were carried out on all the systems for which conducted measurements were made. Some representative samples of the results are shown in this section, which relate to the access systems selected for the illustrations of conducted measurements.

8.1.2.1. Discrete Carrier System

The emissions from an Ascom subscriber modem, measured outside the house at 1m from the house wall are shown in fig 43. It can be seen that the peak emission on the 8.4MHz carrier frequency exceeds the German NB30 limit by 30dB and the MPT1570 limit by 50dB. With this measuring setup, 30dB μ V/m is the noise floor of the measurement equipment.

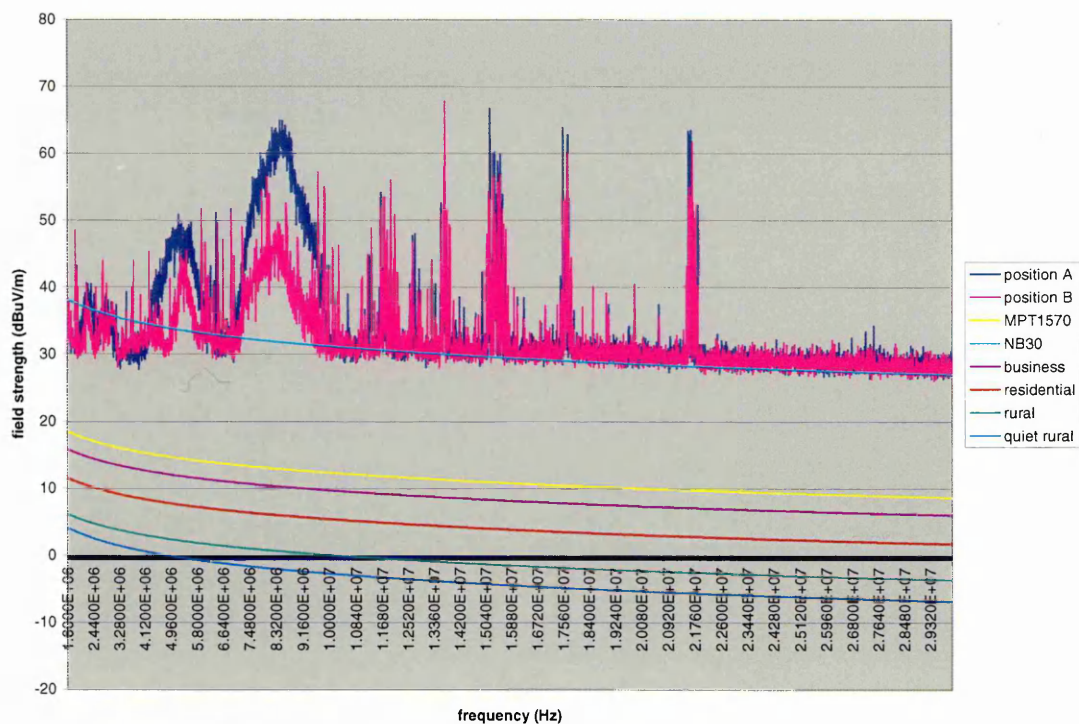


Figure 43: Emissions at Elgin master

8.1.2.2. Spread Spectrum System

Fig 44 shows the emissions from a Main.net subscriber modem. This measurement was taken at a rural location

outside Linz. The antenna was outside at 1m from the building.

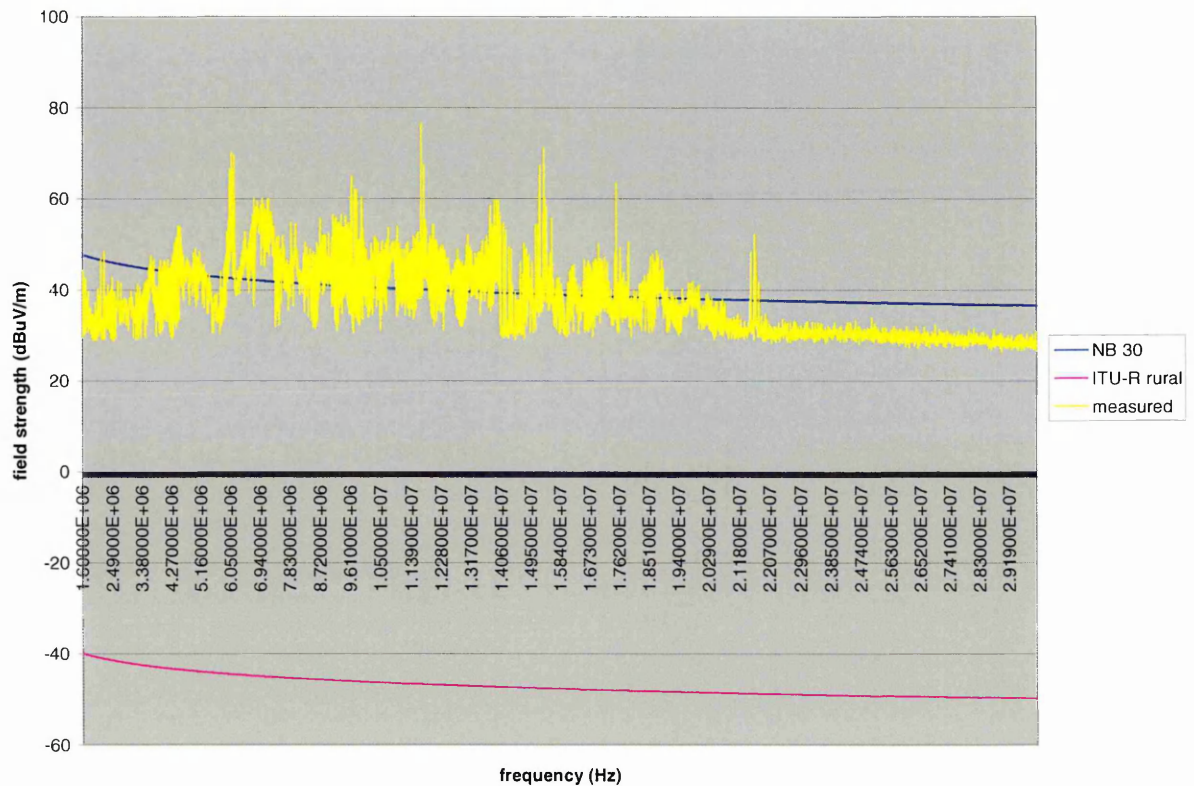


Figure 44: Emissions at Katsengrabstr 71

The UK limits are not plotted on this graph as they are not relevant to Austria. The spread spectrum signal can be seen to exceed the German NB30 limit between 3.8MHz and 19MHz, with some peaks reaching 35dB above the limit. Some of the peaks are broadcast stations with their levels raised by the PLT signal.

8.1.2.3. OFDM Signal

The emissions from an OFDM master (node) modem are shown in fig 45.

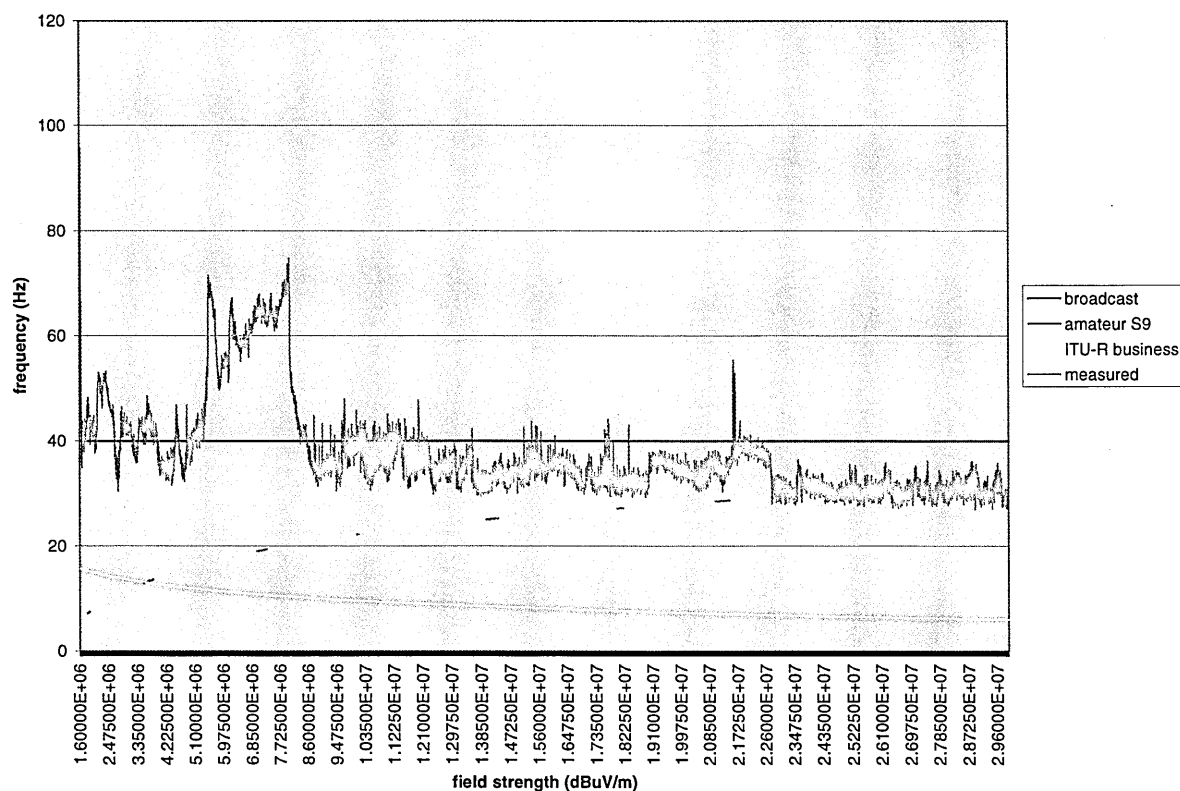


Figure 45: Emission from Hinksman St master

The measurement was made at a master on the system in Quaenbeyan, Canberra. The master was pole mounted and the measurement was taken at a distance of 1m from the pole, directly under the overhead line. The signal peak occurs between 5.33MHz and 8.03MHz, which is the link 3 downstream band, this system using FDM rather than TDM for changing the direction of the signaling. The European limits have not been plotted on this graph because they are not relevant to Australia, which has yet to define a limit, so the radio service signal levels and the ITU-R business district noise level have been plotted (this system was in an industrial area).

It can be seen that the emission from the system exceeds the amateur S9 signal levels on the lower bands and exceeds the broadcast service area limit over a substantial part of the spectrum. For the higher amateur bands above 14MHz, an S9 amateur signal is below the 30dB μ V/m noise floor of the measurement equipment.

8.1.3. Relationship between Conducted and Radiated Limits

In section 4.2, the conducted and emitted limits were explained. The conducted measurements are far easier to make, so that for standards purposes a product approval process based on conducted measurements that could protect radio services would be ideal. The following section uses some of the measurement results to examine the implications of the conducted limits for emissions on some of the networks tested. The following parameters were examined:

- The level of voltage injected by the modem relative to the CISPR conducted limits
- The level of the resulting emissions relative to the MPT1570 limit.

A calculation was performed to find the necessary reduction in injected voltage to conform to the MPT1570 limit, relative to each of the proposed CISPR limits.

The principle underlying this assessment is shown in fig 46.

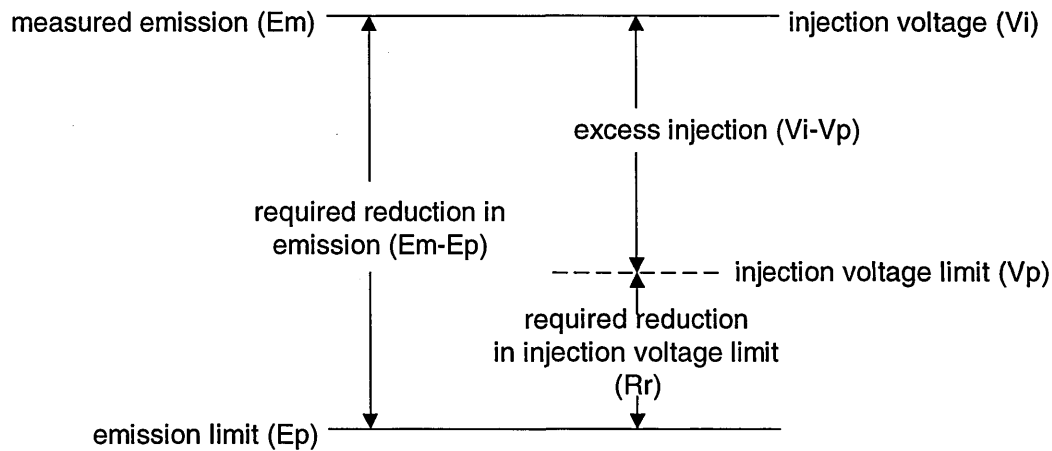


Figure 46: Derivation of equation 28

The measured emissions correspond to the measured injection voltage, which is not necessarily conformant with the appropriate CISPR limit. The excess emission measured therefore consists two elements:

- The amount by which the injection voltage exceeds the CISPR limit ($V_i - V_p$)
- The amount by which the limit needs to be changed to meet the emission requirements (R_r).

This leads to the development of equation 28.

Equation 28; calculation of reduction in conducted limit to meet MPT1570

$$R_r = (E_m - E_p) - (V_i - V_p)$$

where R_r (dB) is the required reduction of the conducted limit to meet MPT1570, E_m (dB μ V/m) is the measured field strength, E_p (dB μ V/m) is the maximum permitted emission under MPT1570, V_i (dB μ V) is the measured injection voltage and V_p (dB μ V) is the permitted injection at the

appropriate conducted limit. The calculation is repeated for each measured frequency.

Fig 47 shows the required reductions in injection voltage to meet MPT1570 at one of the sites tested. It should be noted that the radiated emissions at above 20MHz were close to the noise floor of the receiving equipment used for the wideband scans.

This analysis was carried out for four sites in Scotland and the results were averaged for all frequencies and sites to provide an estimate of the reductions in injection voltage limits needed in order to meet the MPT1570 proposed regulatory emission standard. The average reduction required for each proposed limit is:

Mains port class A:	43.09dB
Mains port class B:	26.97dB
Multipurpose port class A:	57.09dB

From the information presented, it can be seen that the current CISPR 22 limits are too high to protect radio services from PLT emissions and that the proposed multipurpose port limit would exacerbate the situation.

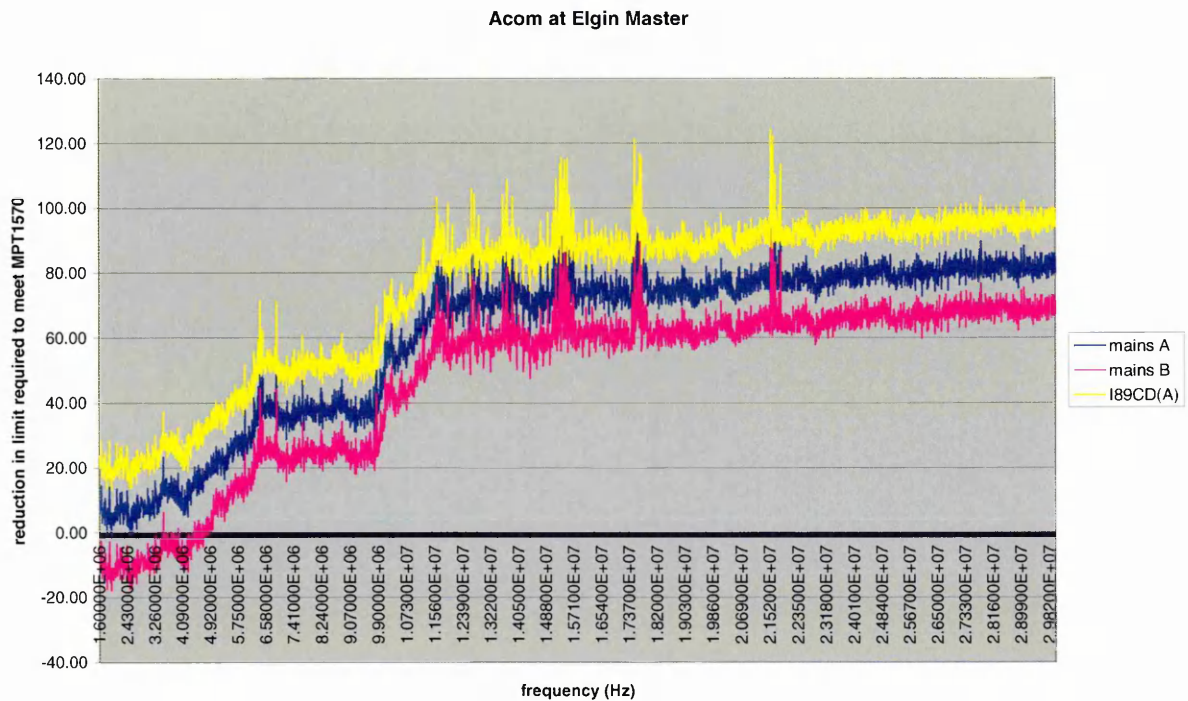


Figure 47: reductions in CISPR limits required to meet MPT1570

8.1.4. Threshold tests

It was only possible to carry out a threshold test on one PLT trial system, which was the Bruce St network in Quaenbeyan, Canberra. This showed that the system was operating at a power level 6dB above that required for satisfactory link performance. Other systems tested have been observed to be set to full power but the thresholds have not been established.

8.2. Characterisation Measurements on Low Voltage

Networks

A number of basic measurements were made on two LV networks in Ipswich, to establish the attenuation and noise characteristics. A spin-off from these measurements has been the calculation of impedances at the measurement ports of the distribution networks. Further measurements for this programme were made on other LV networks without PLT but these did not include attenuation measurements.

For the Ipswich measurements, an underground network and an overhead network were chosen.

8.2.1.Ipswich Underground Network

Most of the measurements were made on the section of network shown in fig 48.

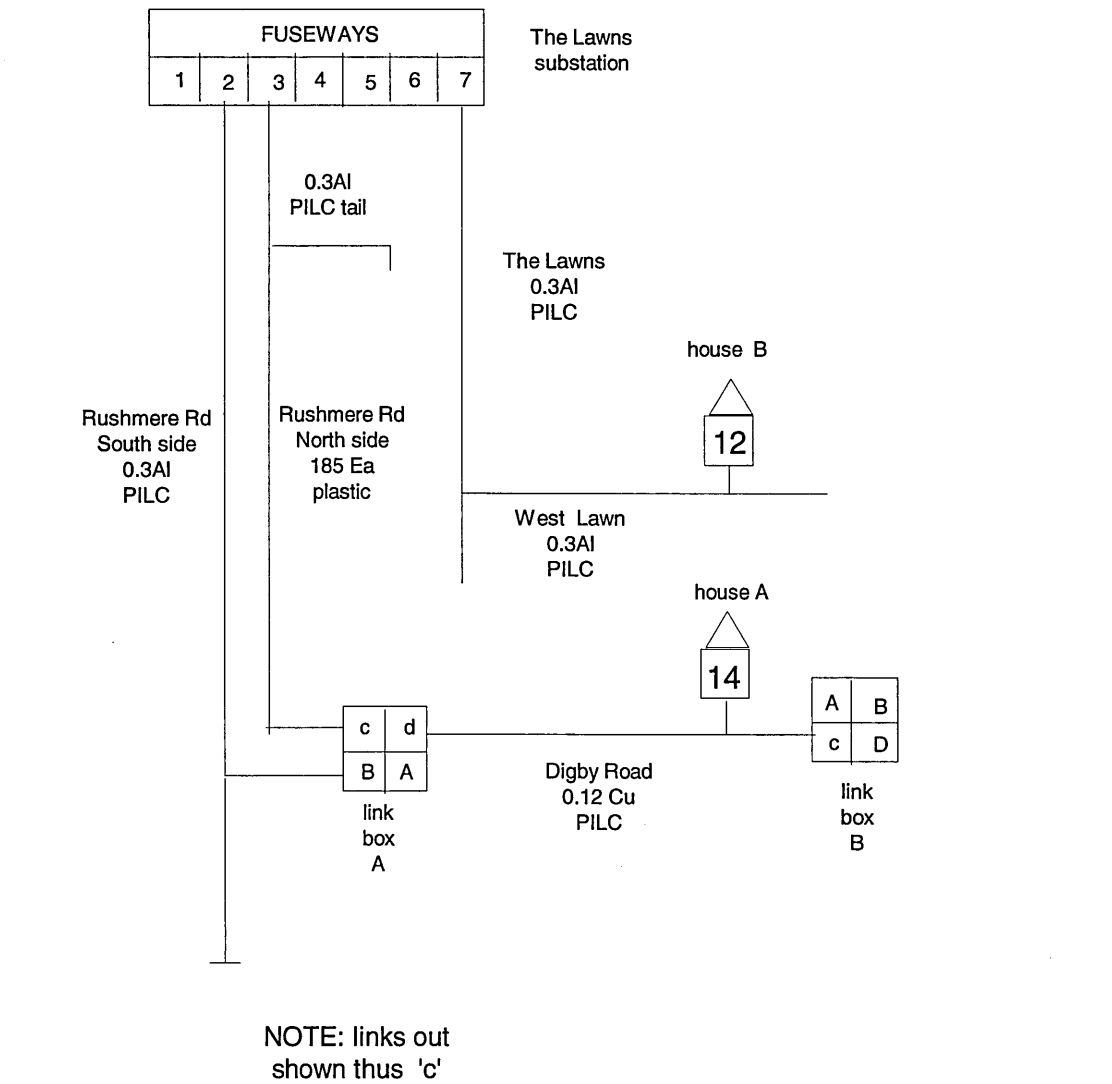


Figure 48: Underground test network configuration

Fig 48 shows the normal running conditions for the section of network that was tested. The Lawns substation has a 500kVA ground mounted transformer and feeds 72 customers via four separate cables. For many of the tests the equipment was located at house A. The network is radially fed and the house is close to the open point, links 'c' normally being left out in link box B. The remaining links in the box are in, providing feeds to other houses from another substation that can be connected to the network to restore supplies in case of

failure of the normal feeding substation. House A has a three-phase service cable, although only a single-phase supply is used. By arrangement with the supply company, connections for the tests were made to the red and blue phases, to allow co-phase and cross-phase measurements to be carried out.

There are two cables from The Lawns substation to link box A that follow a similar physical route. The cable on the North side is a new plastic insulated cable, laid for a scheme to provide underground connections for houses in Rushmere Road that were previously served by overhead mains. It is connected to fuseway 3 of the substation via a short PILC cable tail that originally fed the overhead system at a pole close to the substation. It terminates on way c of link box A, which is left open under normal conditions. The new cable was laid just before the tests commenced and provided an excellent opportunity for comparative measurements of the performance of similar lengths of different cable types, by measuring from the substation to ways c and B of link box A. The houses fed from the new cable were converted from overhead feed to underground by running cables up the outsides to the original electrical intake position; this is known as skeletal wiring and provided another opportunity for emission tests.

Measurements were also made between house B and the substation. House B is served by another underground feeder, connected to a different fuse way in The Lawns substation.

8.2.2.Overhead Network

Tests were also carried out on an overhead network fed from a substation at Church Close, Rushmere. Access was gained for testing at 'The Garland' public house, which was close to the network open point in Humber Doucy Lane. This network is shown in fig 49. In the figure, which is scanned from the Eastern Electricity 1:500 mains records, the poles are shown with their interconnections. The pole in Humber Doucy Lane with an arrow pointing to it is the normal open point between Church Close and the next substation. This can be closed by installing jumpers to provide a feed from another substation if the normal feed fails. During the tests the network was running normally, without this interconnection. Since the tests were carried out this overhead network has been removed because of corrosion of the steel poles, and replaced by an underground network.

Fig 50 shows the type of construction used for the line that was tested. The line consists of four uninsulated conductors, set at a spacing of 10cm. The top three wires are the phase conductors, the fourth conductor at the bottom being the neutral. In the background two

wires can be seen going from left to right; this is a cross-road service connecting a house to the main. The single wire visible in fig 50 is a BT drop wire (house service) and has no connection with the PLT tests.

Figure 49: Church Close Overhead Network



Figure 50: Overhead LV Line construction

8.2.3. Types of Measurement

The following measurements were performed on the networks:

- Attenuation and Impedance
- Steady State Noise (ingress noise)
- Transient Noise (underground network of fig 47 only)
- Emissions

The purpose of these tests was to assess the level of performance that could be achieved using propriety transmission equipment consisting of cable TV modems and the associated network node.

8.2.4. Tests Performed

This section explains the rationale of the measurements and their relevance to the research programme.

8.2.4.1. Attenuation and Impedance

Attenuation and impedance measurements were carried out to establish the following parameters:

- The variation of attenuation with cable types

- The isolation between separate phases in the same cable (phase coupling)
- Whether the attenuation varied with the electrical loads, as is found with LF systems
- The loss across a link box, to provide a figure for inter-network isolation.

Attenuation measurements were made on the network shown in fig 47 as follows:

- House A to link box A
- House A to link box B
- House A to substation co-phase
- House A to substation phase coupling (transmitting on blue phase and receiving on red)
- House A to the far side of link box B
- Substation to link box A via the paper cable
- Substation to link box A via the plastic cable.
- House B to substation.
- During daylight and after dark between house A and link box A.

Tests were also carried out between Church Close substation and the Garland Inn on the overhead network shown in fig 49.

8.2.4.2. Emissions

K factor measurements were carried out as follows:

- House A.
- Lamppost adjacent to link box A, approximately 100m from house A, at which the RF source was located.
- Houses with skeletal wiring located between link box A and the substation on the North side of Rushmere Road, at approximately 150m from house A, at which the RF source was located.
- Overhead network, at positions close to the substation and in the car park of the Garland Inn where the conducted measurements were made, which was close to the open point.

The locations for the tests on the underground network in the vicinity of house A are shown in fig 51 (which is taken, with permission, from the RA report).

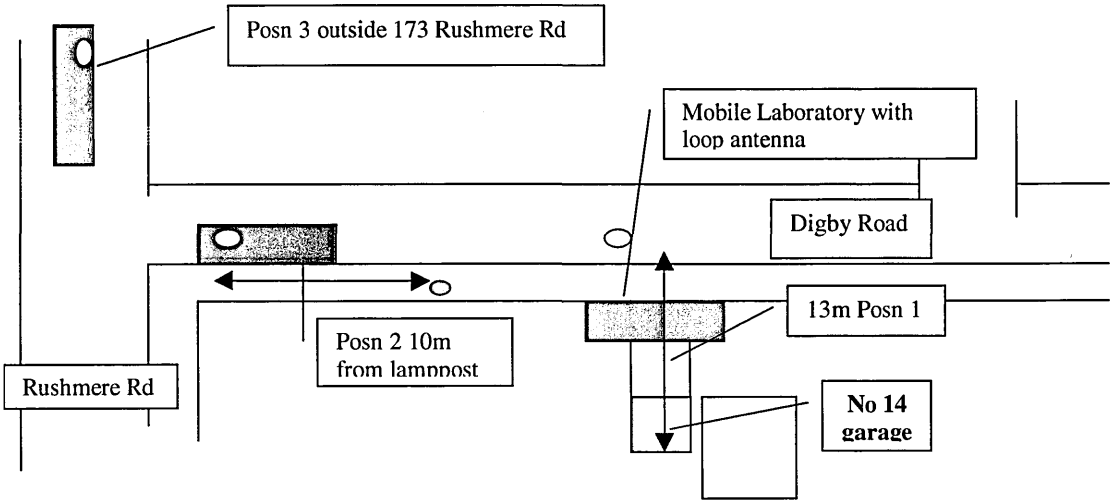


Figure 51: Locations for emission tests close to house A [Bull, E, 1998]

For the measurements shown in fig 51 the RF signals were connected at the service position of house A (#14 Digby Road in the figure). The test positions were chosen to provide information on the emissions from the features listed in table 11.

Table 11: Emission test positions for the underground network

position	Principal radiating structure
1	Detached house with normal underground service cable
2	Concrete lamp standard
3	Detached house with skeletal wiring (conversion from overhead feed with lead-ins extended down wall to connect to new underground service)

Figs 52 & 53 (which are taken with permission from the RA report) show the positions used for the tests on the overhead network shown in fig 49.

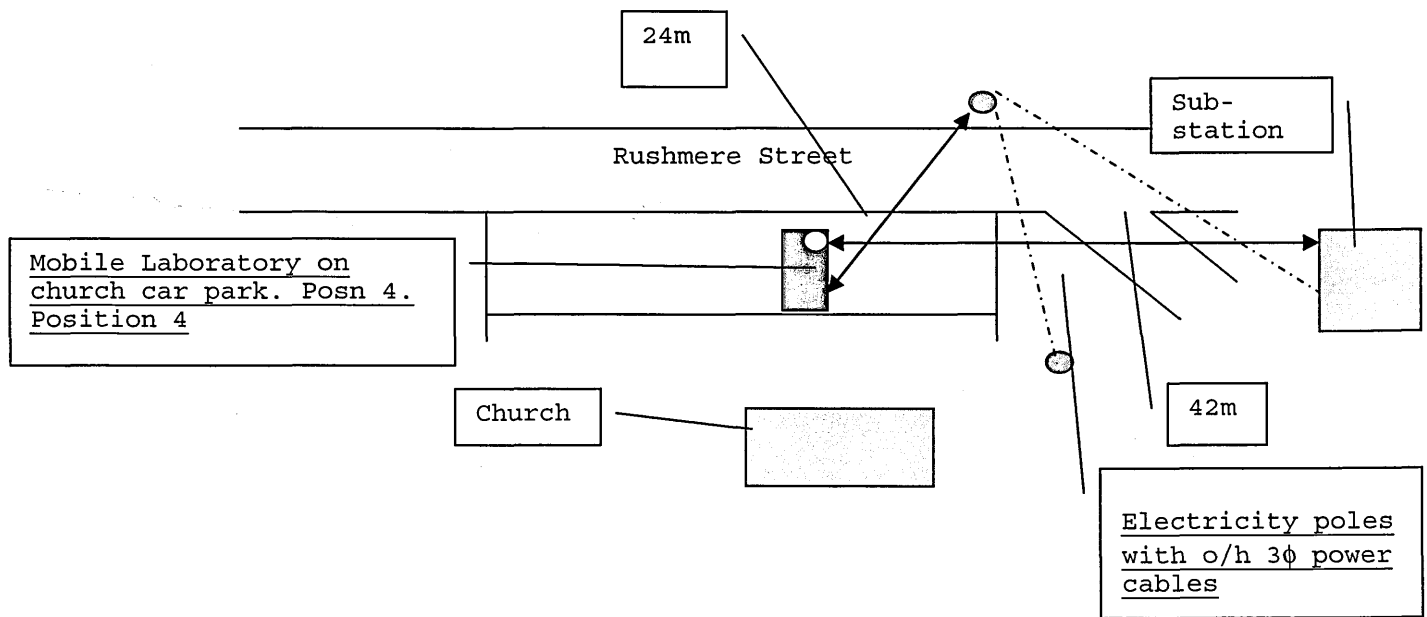


Figure 52: Test locations on the overhead network at Rushmere Church [Bull, E, 1998]

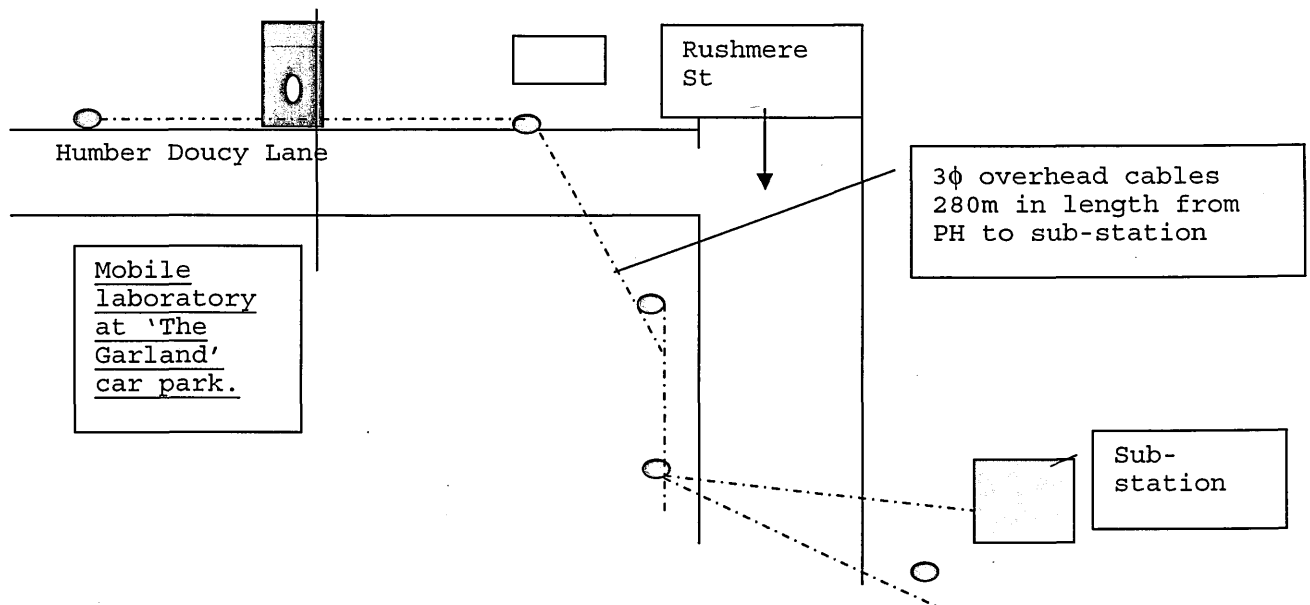


Figure 53: Test position on overhead network at The Garland Inn, Rushmere [Bull, E, 1998].

8.2.4.3. *Ingress Noise*

Ingress noise measurements were made at three substations, two houses and a link box. At house A, measurements were made at night and during the day, to provide an assessment of the diurnal variation in ingress level.

8.2.5. Results

This section details the results of the measurements.

8.2.5.1. *Attenuation*

The results of the attenuation measurements are described in this section. For each measurement made, a graph is presented that shows the attenuation (loss) in dB and phase shift (angle) in degrees, plotted against the measurement frequency. The frequency step between measurements is 50kHz. The attenuation measurements are also presented in tabular form, showing the average loss within each of the 3MHz bands used for later analysis. For the cable measurements, the equivalent loss per 100m for each 3MHz band is also shown, taking account of the length of cable on which the measurements were made, to facilitate comparisons and calculations.

While the primary interest in the attenuation measurements for this thesis is the loss figures, the

phase shift is potentially significant in the choice of modulation for PLT systems. The graphs presented in this section illustrate the extreme variability of the phase shift that would be experienced for PLT transmission.

8.2.5.1.1. House A to Link Box 'A'

Fig 54 shows the co-phase loss between house A and link box A. This part of the route consists of 115m of 0.12in² copper-cored, Paper Insulated Lead Covered four-core cable, with 13 houses connected. The mean loss in selected frequency bands is as given in table 12.

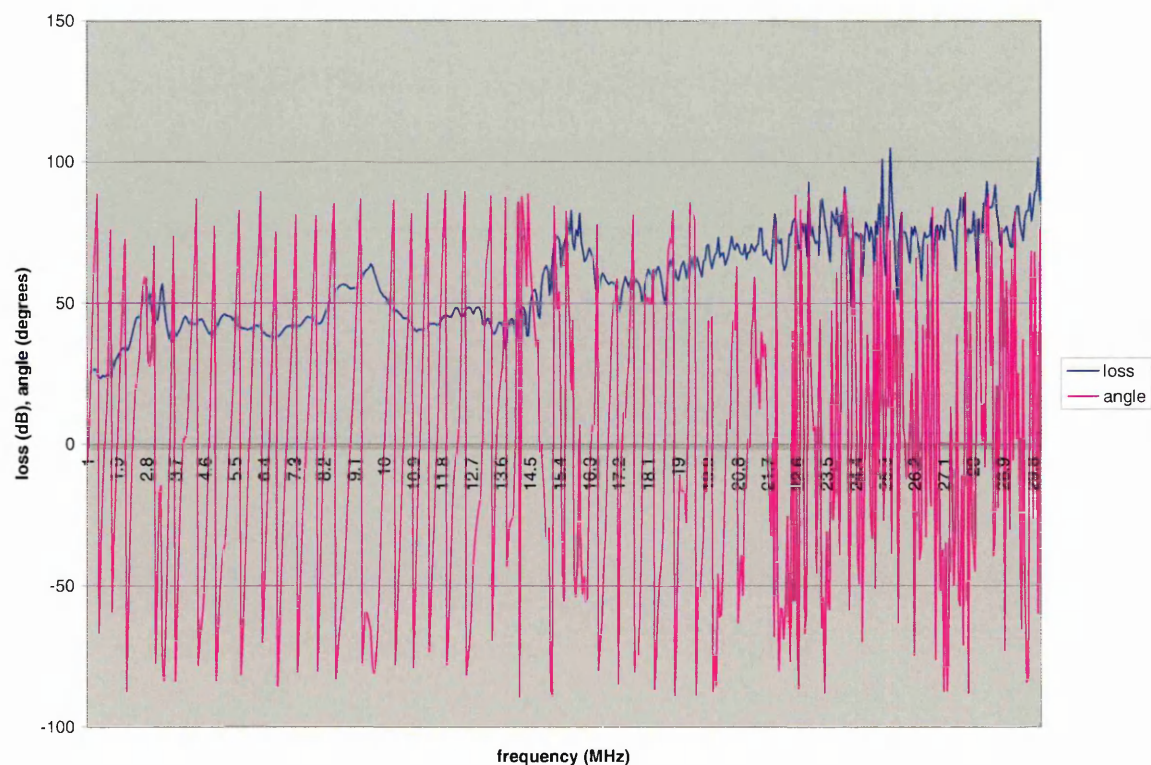


Figure 54: Co-phase loss between house A and link box A

Table 12: mean loss per frequency band between house A and link box A

Frequency Band	Loss on Section (dB)	Loss /100m (dB)
1-4	37.4	32.5
4-7	41.6	36.2
7-10	50.7	44.1
11-14	43.6	38.0
14-17	59.5	52.1
17-20	59.5	51.8
20-23	70.4	61.3
23-26	75.0	65.2
26-30	77.4	67.3

8.2.5.1.2. House A and The Lawns Substation

A number of measurements were made over the whole route from house A to the feeding substation, a route distance of 240m. The co-phase loss is shown in fig 55 and table 13 gives the mean loss in various frequency bands.

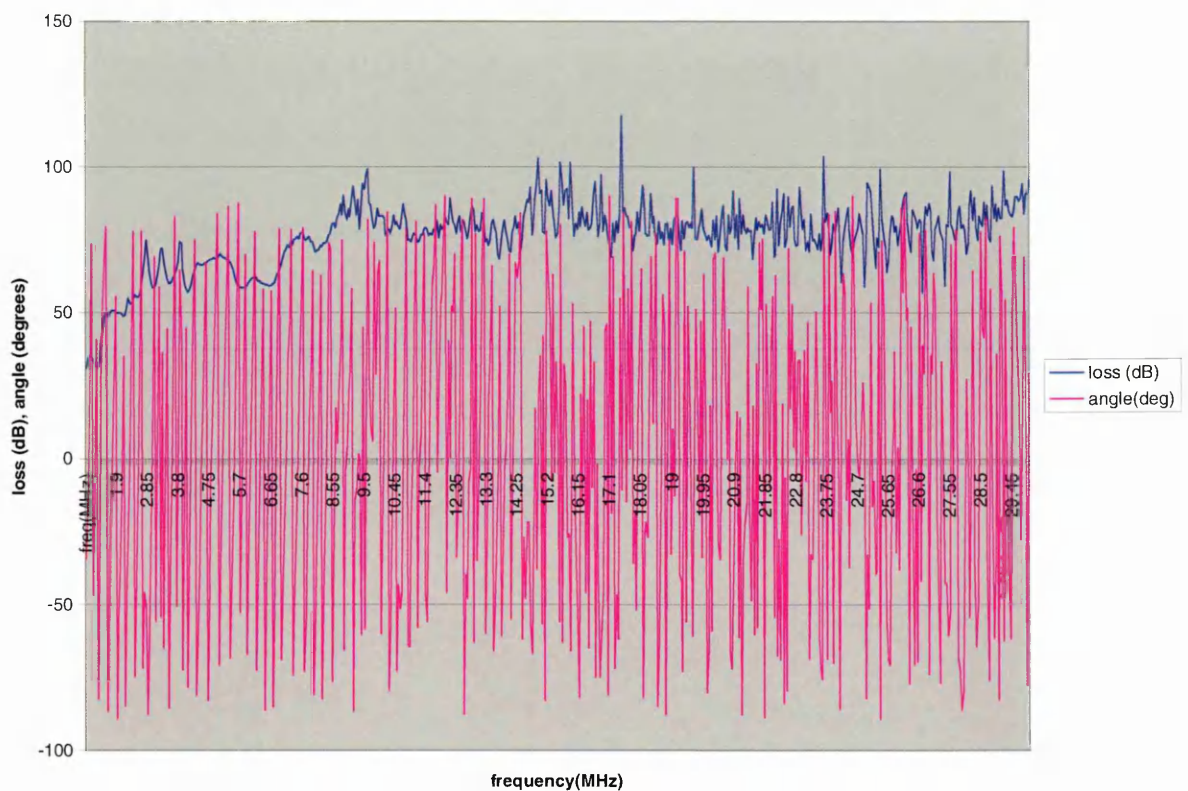


Figure 55 Co-phase loss between house A and substation

Table 13 - Mean loss per frequency band between house A and substation

Frequency Band	Loss on Section (dB)	Loss /100m (dB)
1-4MHz	54.4	22.7
4-7MHz	63.3.	26.4
7-10MHz	79.7	33.2
11-14MHz	78.5	32.7
14-17MHz	84.3	35.1
17-20MHz	80.3	33.5
20-23MHz	79.3	33.0
23-26MHz	77.7	32.4
26-30MHz	82.1	34.2

8.2.5.1.3. Link Box A to the Lawns Substation

Measurements were made between link box A and the substation because it was possible to obtain access to two different types of cable with closely similar route lengths. The attenuation measured is shown in fig 56, with a comparison by frequency band in table 14.



Figure 56: Comparison of attenuation of plastic and paper insulated cables between link box A and The Lawns substation

Table 14: Mean loss in various frequency bands: link box A to substation

Frequency band	Paper cable (0.3mm ² Al)		Plastic cable	
	Loss in section (dB)	Loss/100m (dB)	Loss in section (dB)	Loss/100m (dB)
1-4MHz	33.6	27.3	37.5	30.5
4-7MHz	44.9	36.5	49.8	40.5
7-10MHz	46.6		67.2	54.6

8.2.5.1.4. Loss Across a Link Box

Measurements were made to establish the loss across link box B with the links out. This was done by injecting a signal at house A and measuring first on the house side

of way c and then on the links inserted in the box. As links were not fitted to way c this provided a measurement across an open link. The results of the two sets of measurements were then subtracted and plotted, as shown in fig 57 and table 15.

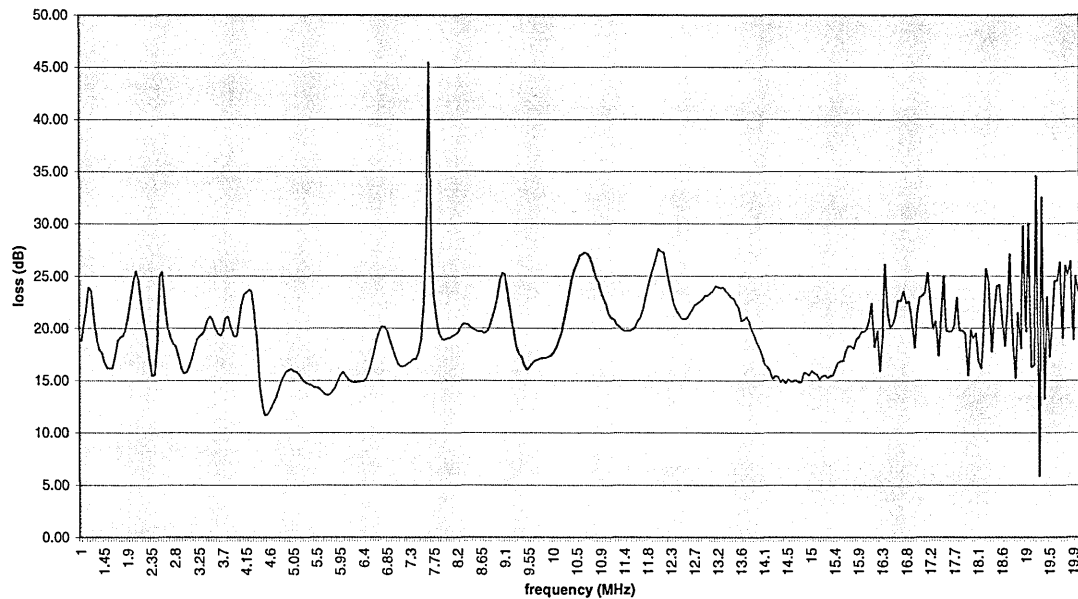


Figure 57: Loss across link box B; open links

Table 15: Mean loss in frequency bands across open link box B

Frequency band (MHz)	Loss (dB)
1-4	19.58
4-7	16.21
7-10	19.87
11-14	22.25
14-17	17.82
17-20	21.43
20-23	20.71
23-26	26.69
26-30	16.55

8.2.5.1.5. Phase Coupling Loss

If the phases in an underground cable could be used to transmit separate PLT signals, the data capacity would be three times that available if the coupling between phases was too high. Measurements of the loss between phases in the cable were made from house A to the substation and to link box B. On each route, first a measurement was made on the same phase (co-phase). The measurement was then repeated between phases (cross-phase), using a coupler connected to the red phase at the house (RX) and the remote coupler connected to the blue phase. The phase coupling loss (loss between phases) on the route was then found by subtracting the co-phase loss measurement from the cross-phase loss measurement. This method of providing a figure for far-end phase coupling loss was preferred to measuring between two phases of the house service, because the method used is more likely to provide a figure for the network, rather than the service cable. It also avoided the possibility of fortuitous coupling in the unscreened power cables between the couplers and the service cable within the house.

The results of this test are shown graphically in fig 58 and by frequency bands in table 16.

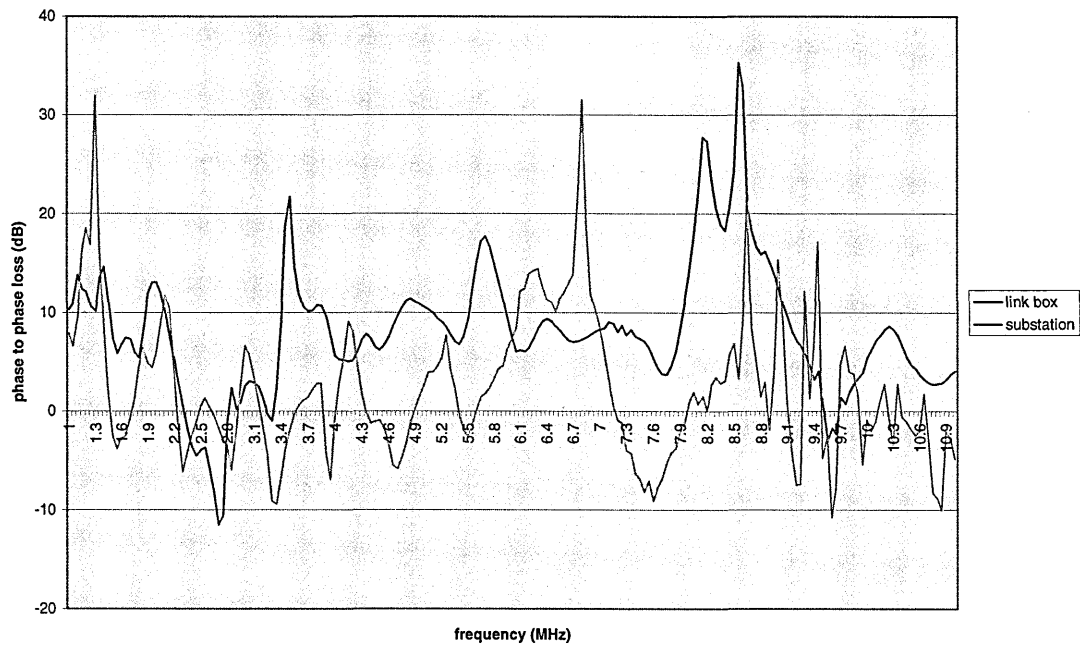


Figure 58: Phase coupling loss

Table 16: Phase coupling loss by frequency bands

Frequency band (MHz)	Loss measured at link box(dB)	Loss measured at Substation(dB)
1 - 4	5.96	2.31
4 - 7	8.85	5.49
7 - 10	10.6	0.89

It can be seen clearly from the table that the phase coupling loss is lower on the substation route than on the link box route. It should be noted that the lower losses equate to increased coupling. The distance to the substation is almost ten times the distance to link box B and the coupling to the shorter route would be expected to be lower, whether it is the result of capacitance or mutual inductance between the cable cores. Whatever the reasons for the coupling, it can be seen that at HF the cable effectively has a single core; there is no

possibility of using the three cores in the cable to carry different data streams on the same carrier frequencies.

8.2.5.1.6. House B to The Lawns Substation

House B is located approximately 110m from the substation, fed by a five-core⁹ 0.3 in² aluminium cored PILC main serving a number of houses. The loss is shown graphically in fig 59 and by frequency bands in table 17.

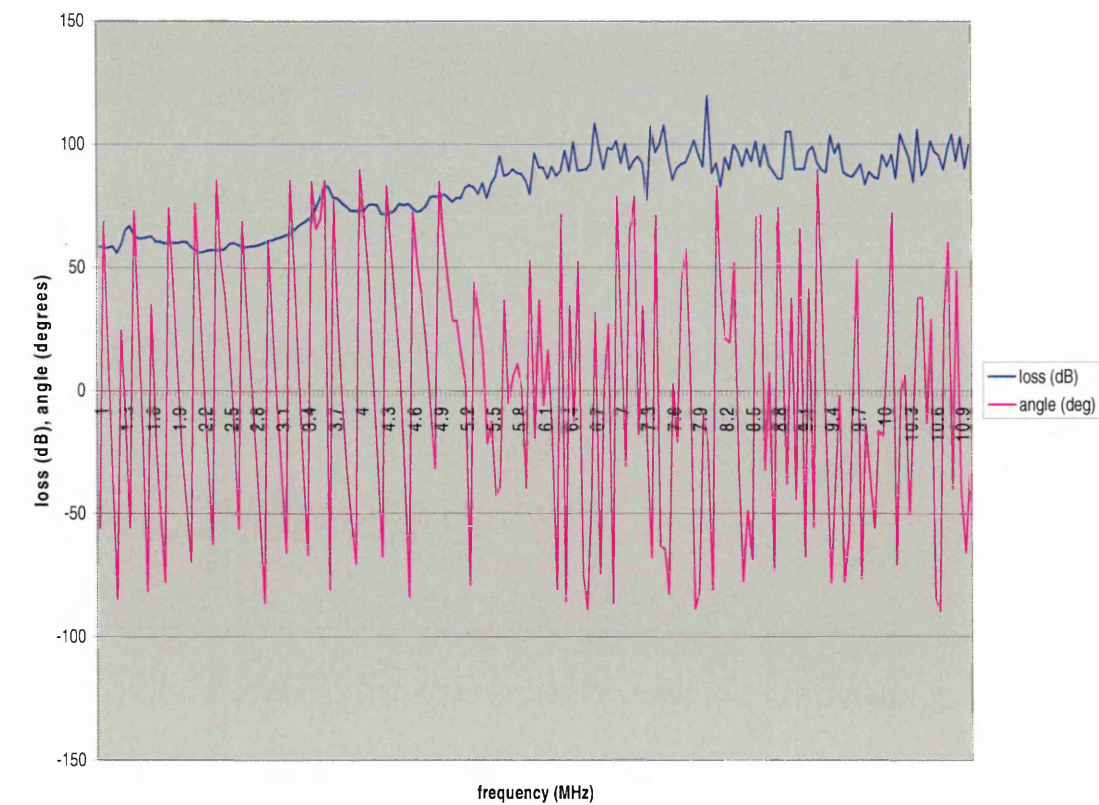


Figure 59: loss between house B and The Lawns substation

⁹ the fifth core is used to control street lighting from a common timeswitch

Table 17: Loss from house B to The Lawns by Frequency Bands

Frequency band (MHz)	Loss (dB)	Loss/100m (dB)
1 - 4	63.28	57.53
4 - 7	84.02	76.38
7 - 10	93.7	85.18

8.2.5.1.7. Overhead Network Loss Between Church Close
Substation and 'The Garland' Inn

Measurements were made to determine the loss on the overhead network. A local coupler was attached to the busbars at Church Close substation, where the network analyser was located, and coaxial cable was run to 'The Garland' Inn, where the remote coupler was plugged into a 13A socket outlet in the bar. Because the phase to which the socket outlet was connected was not known, attenuation measurements were taken on all three phases in the 1MHz to 3MHz frequency range and the mean attenuations recorded are shown in table 18.

Table 18: Mean loss on overhead system in the range 1MHz to 3MHz

Phase at substation	Loss on run (dB)
red	70.75
yellow	74.48
blue	77.7

The following deductions can be made from the data in the table:

- The socket outlet tested was connected to the red phase, because the loss is lowest on red phase.
- The phase coupling is high; with a mean loss of the order of only 3.73dB between the red and yellow phases, which are adjacent on the poles, and 6.95dB between the red and blue phases, which are the most widely spaced.

On the above basis, the loss on the red phase is presented in fig 60 as being representative of the performance of an overhead network. Table 19 shows the average loss in the frequency bands tested. Because of ingress noise, measurements were not made above 6MHz.

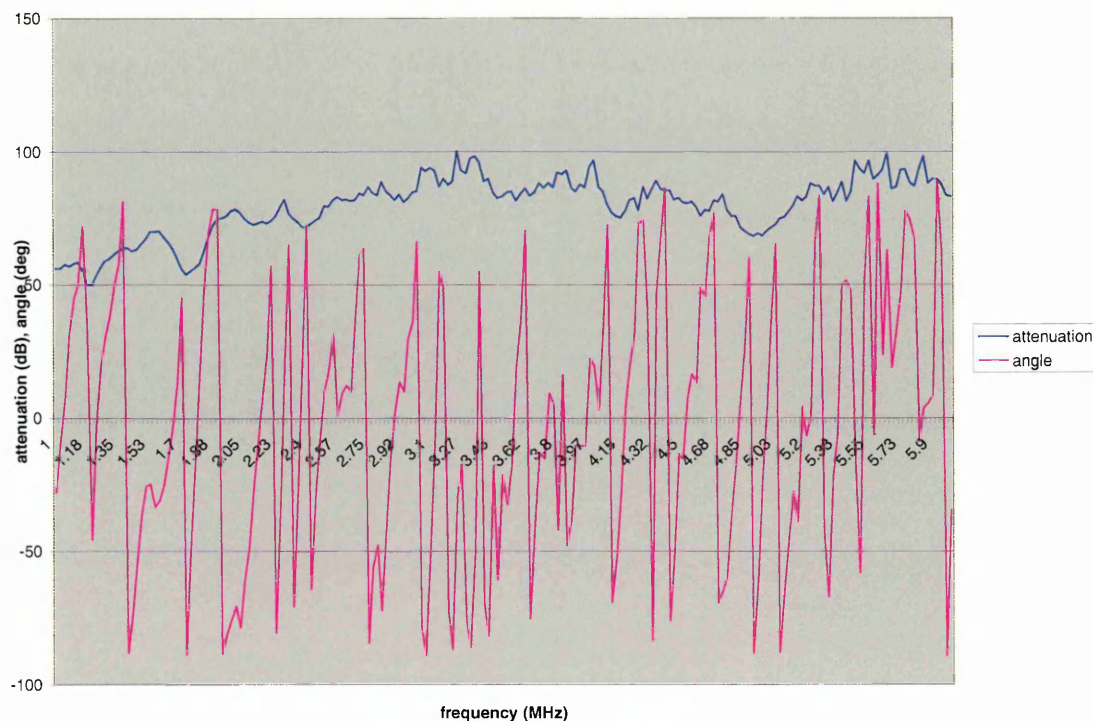


Figure 60 Loss on overhead network

Table 19 Loss on Overhead System by Frequency Bands

Frequency band (MHz)	Mean loss between substation and 'The Garland' (dB)	Mean loss/100m (dB)
1 - 4	76.8	32.3
4 - 6	83.1	34.9

8.2.5.1.8. Diurnal Variation of Attenuation on
Underground Network

Tests in the Low Frequency access band (9kHz to 95kHz) have shown a difference of 20dB between the day attenuation and night attenuation between house A and the substation [Brannon 1995 pp155]. This was found, by modeling, to be associated with the effect of resonant loads formed by the power factor correction capacitors in the street lamps and their service cables [ibid pp38 - 40], the effect being present only when the street lamps were operating. It was therefore decided to carry out attenuation tests at HF on a given section of main before and after dark, to see if any load related effects altered the attenuation. For safety reasons, the test was restricted to the section between the house A and link box A, rather than measuring over the whole route from the house to the substation. Fig 61 shows the difference between the night-time loss and daytime loss over the measured frequency range. Measurements were not

made above 20MHz due to excessive ingress noise levels affecting the results of the attenuation measurement, the cause of which was not resolved.

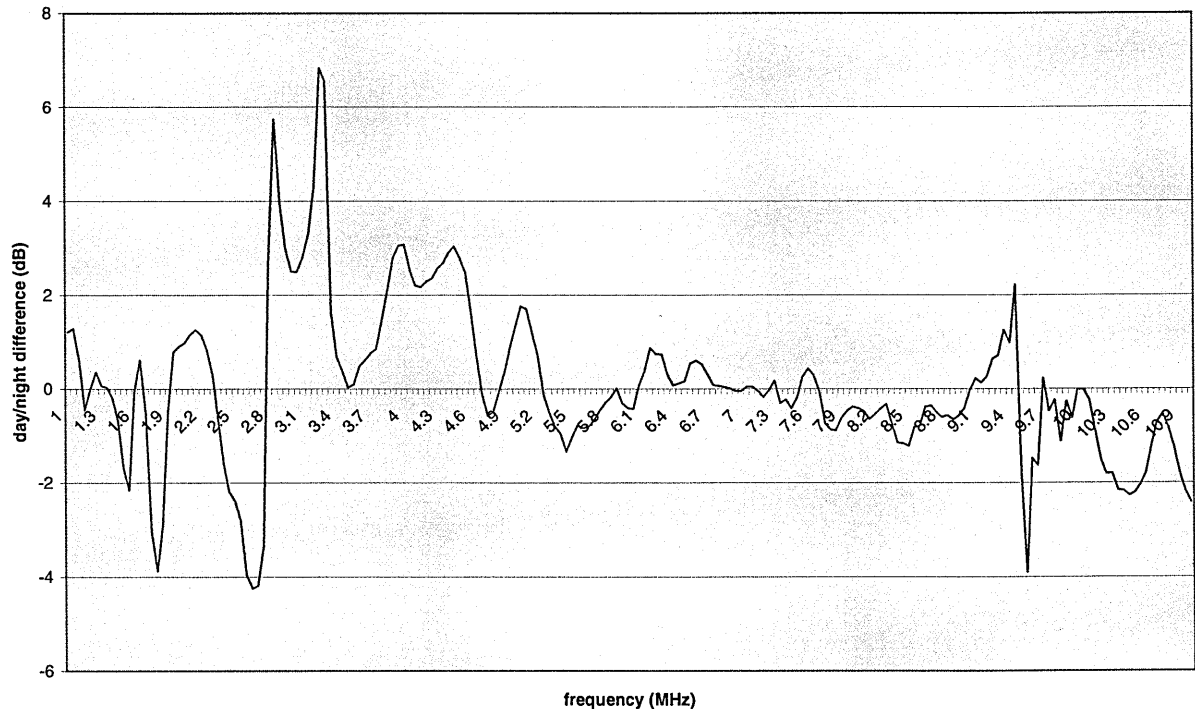


Figure 61 Attenuation difference day/night - house A to link box A

The mean difference across the whole measured frequency range 1MHz to 20MHz is -0.01dB, which is well below the measurement uncertainty. The mean differences by frequency band is shown in table 20.

Table 20: Mean day-night differences in attenuation by frequency bands

Frequency band (MHz)	Day/night difference in attenuation (dB)
1 - 4	0.49
4 - 7	0.6
7 - 10	-0.36
11 - 14	-0.86
14 - 17	0.18
17 - 20	0.36

It can be seen from fig 61 that there are some high-Q variations well above the average at spot frequencies, with a maximum difference of 7dB at 3.4MHz. These are assumed to be caused by the switching of loads changing the impedance presented at the main by the service cables. It is assumed that the capacitance of domestic loads tunes with the service cable inductance to produce impedance differences at the service tap that cause the high-Q effects seen in fig 61. Power factor correction capacitors are too high in value for their effect to be seen in the HF band, but some motorized appliances contain suppression capacitors that may cause resonance at higher frequencies.

Because practical broadband PLT systems use wideband modulation it is the average variation in loss within the 3MHz analysis bands that is important, and at less than 1.0dB for any of the bands these values are low compared to the 100m mains loss figures, so that the effect on transmission performance will be negligible. The results obtained show that for the purposes of the design of broadband PLT systems the attenuation may be assumed to be constant despite load variations.

8.2.6. Emissions

Emission measurements were made at a number of above ground structures (houses and street furniture) connected to the underground network. Measurements were made on the overhead network to establish the level of emission and the k factors for the overhead mains.

8.2.6.1. Underground Network

The results of the emission tests on the underground network are shown in table 21. This table was prepared from the data measured by the Radiocommunications Agency [Bull, E, 1998]. Unlike the RA results, table 21 incorporates a correction for attenuation in the mains network, which raises the emission values compared with what was measured. The correction is required because the point of injection for all measurements was house A, so that the injection power was not constant at each location measured. Because the mains attenuation had been measured it was possible to calculate a correction factor for each point of measurement. It should be noted that in the case of the house with skeletal wiring the links were out in the link box between the mains to which the injection and measurement points were connected, so that an allowance is included for the loss across the

open links. The corrected figures in the table therefore give the emission levels for 10dBm of injection.

Table 21: Emission measurements on underground network

freq (MHz)	emission (dB microvolt/m)							
	house with signal generator	lamp post			house with skeletal wiring			
		measured emission	system loss (dB)	corrected emission	measured emission	link box loss (dB)	cable loss (dB)	corrected emission
2.3	60.4	37	34	71	35	20	34	89
2.9	63	42	50	92	40	16	50	106
4.95	57	41	45	86	32	15	45	92
5.42	50.5	40	40	80	35	14	40	89
6.9	62.5	41	40	81	34	20	40	94
8.9	67	40	55	95	33.5	20	55	108.5
10.9	59	38	40	78	34	23	40	97
13	55	32	42	74	34			
16.5	57	40	57	97	32			
18.6	50	40	65	105	33			
19.3	59	40	60	100	33.5			
20	56.5	33			30			
25	60	30			25			
29.5	61	29			34			

The shaded areas in the table indicate that measurements could not be made at those frequencies because the emission levels were too low compared to the level of broadcast signals. This was a result of the mains attenuation between the feed and measurement points.

For PLT systems, it is common to express the relationship between the power injected and the resulting emission as a term described as 'k factor'. This allows the emission from buildings and street furniture to be predicted if the injected power is known. The results in the table were converted to k factors at the standard measurement distance of 1m used in the MPT1570 emission standard for PLT [MPT1570]. The method of expressing k factor used is that described by the Netherlands Radiocommunications Agency [Wirth 2003].

The results are shown graphically in fig 62.

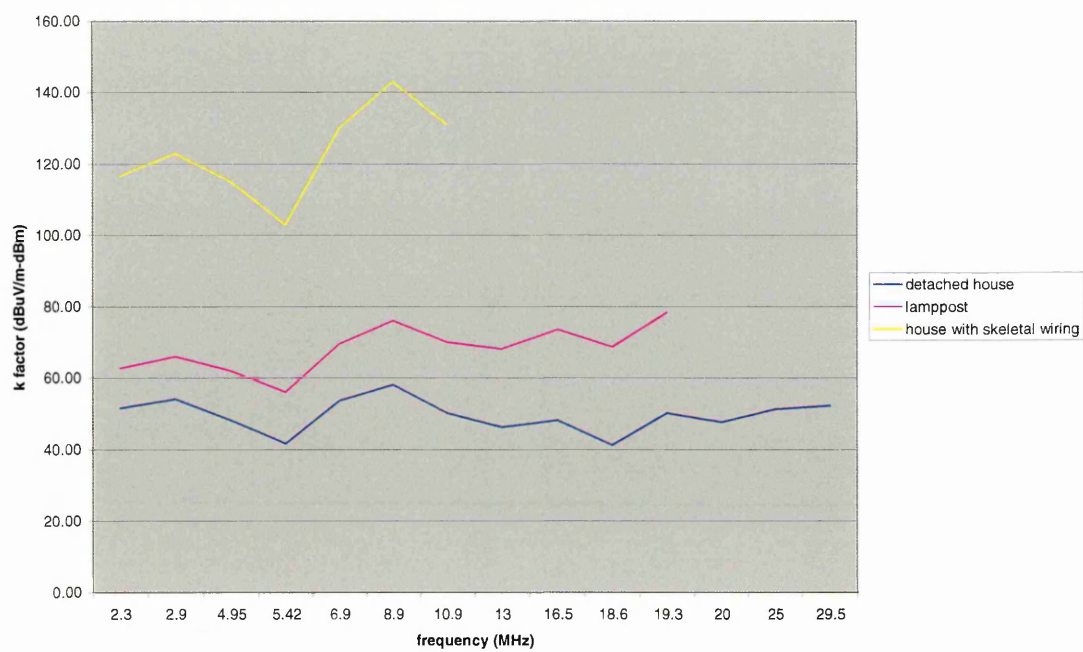


Figure 62: k factors for houses and street furniture

The k factors in the frequency bands used for the attenuation measurements were extracted from the data set used for the graph, and are shown in table 22.

Table 22: k Factors by Frequency Band

Band (MHz)	Detached house dB μ V/m-dBm	lamppost dB μ V/m- dBm	House with skeletal wiring dB μ V/m-dBm
1 - 4	52.84	64.30	119.74
4 - 7	47.81	72.47	115.99
7 - 10	53.97	71.73	134.61
11 - 14	48.14	68.95	
14 - 17	48.14	73.50	
17 - 20	46.47	73.47	
20 - 23	47.64	10	
23 - 26	51.14		
26 - 30	52.14		

It is interesting to note that the objects with a clear vertical conductor appear to radiate more efficiently than the detached house. The house with skeletal wiring was of a similar size to the other house but differed because of the high service intake position with external vertical conductors, despite having an underground feed from the main to the wall of the house. The lamppost is, of course, completely vertical but far smaller in area than a house.

A further k factor measurement is available, which was made with the Open University Power Systems Communications Research group at the Scottish and Southern Energy headquarters [PSCRG 2003]. A measurement was made at 5MHz at 1m distance, and yielded a k factor of 51.65 dB μ V/m-dBm. This is close to the value of 47.81 dB μ V/m-dBm obtained for the detached house in the

frequency range 4 - 7 MHz [table 22], despite the large difference in the relative sizes of the buildings.

8.2.6.2. Overhead network

Table 23 shows the results of the measurements made at Rushmere Church [fig 52] and the k factors calculated from them. For the purposes of the table, the measurements are shown in the analysis sub-bands used for this study. As a measurement was not taken for the 20MHz - 23MHz band the geometric mean of the results for the 17MHz - 20MHz and 23MHz - 26MHz bands has been used.

Table 23: Overhead system emissions and k factors

subband (MHz)	24m field strength (dBuV/m)	1m field strength (dBuV/m)	k factor (dBuV/m- dBm)
1 - 4	48.2	75.8	65.8
4 - 7	37.8	65.4	55.4
7 - 10	41	68.6	58.6
11 - 14	41	68.6	58.6
14 - 17	33	60.6	50.6
17 - 20	35.8	63.4	53.4
20 - 23	37.8	65.4	55.4
23 - 26	40	67.6	57.6
26 - 30	42	69.6	59.6

8.2.7. Ingress Noise

Scans of two typical ingress noise plots are shown in figs 63 and 64. Both of these plots relate to house A;

fig 63 is a daytime plot, taken at 13:00hrs and fig 64 is a night-time plot, taken at 20:00hrs on the same day, 20 March 1998. Both of these plots were taken with a resolution bandwidth of 10kHz, using the spectrum analyser's peak hold function.

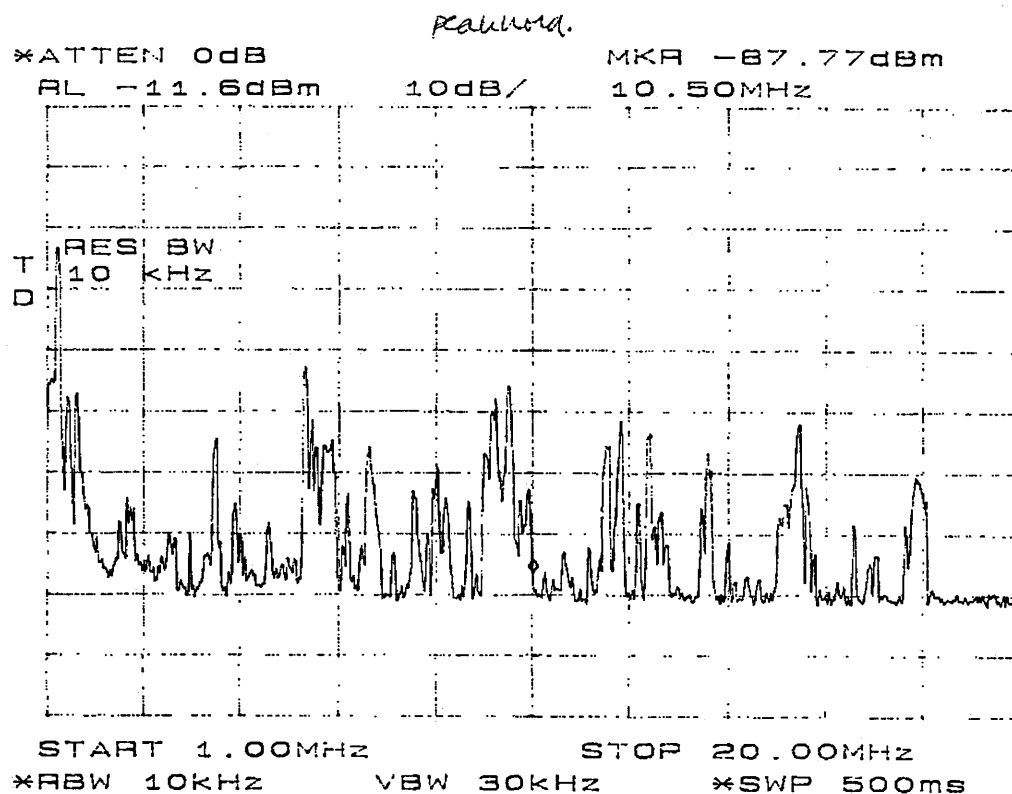


Figure 63: Daytime ingress noise plot at house A

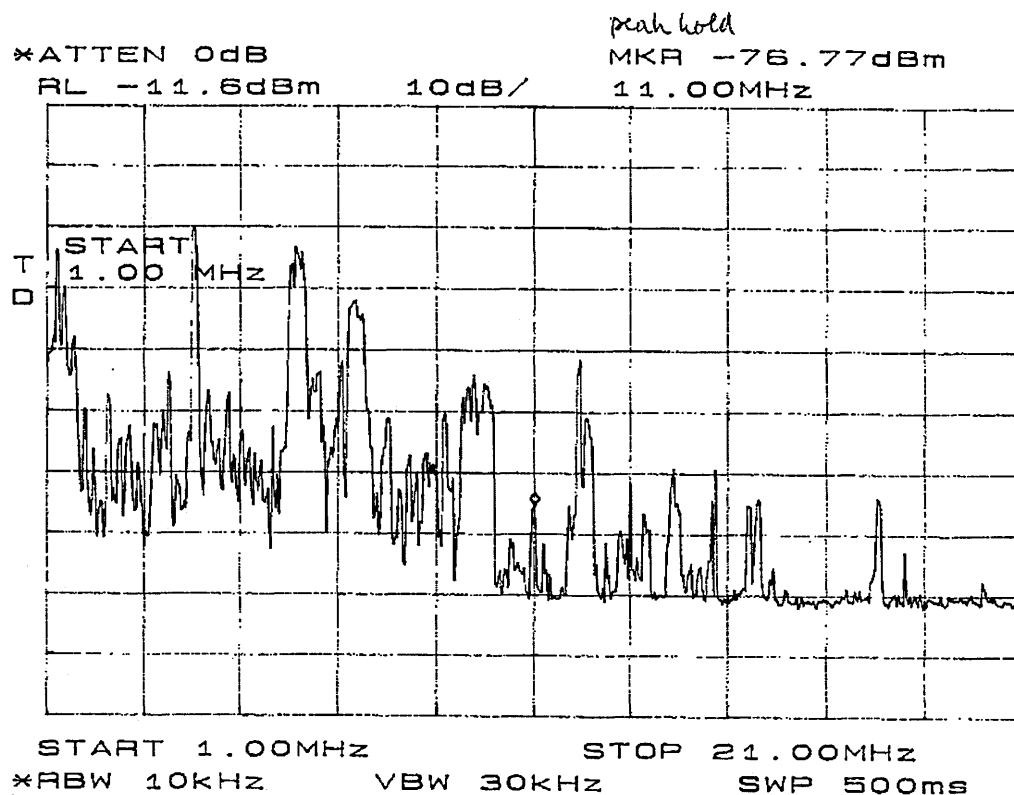


Figure 64: Night-time ingress noise at house A

The ingress noise is caused by to the reception of broadcast radio stations (intentional radiators) by the mains wiring. It can be seen that the signal levels lay below -61dBm during the day, but at night some signals exceed -41dBm. The peak at the left-hand side of each plot, with a constant level of around -35dBm is the local IBA station, Radio Orwell¹⁰, which operates on 1170kHz with 0.28kW EMRP¹¹ from Foxhall Heath, a distance of 3.25km from the house at which the measurement was made. Because of its proximity to the house, this service will

¹⁰ now known as Amber Radio

¹¹ Effective Monopole Radiated Power

be using ground wave propagation and thus not subject to day/night variation in level resulting from changes to the ionosphere.

A number of similar measurements were made at various points on the networks tested in Ipswich, and the recorded ingress noise levels by frequency band are shown in table 24, which also includes the results of some additional measurements made by the PSCRG on other networks. For Ipswich, in addition to the ingress noise by frequency bands this table also shows the level of the Radio Orwell signal at each measurement position, as the station acts as a convenient reference signal. The non-Ipswich measurements were at the locations described in the table as Woolley Hall, Elgin and Mycroft. The PSCRG ingress noise measurements were made using a measuring receiver rather than a spectrum analyser and plotter. This provided a more accurate measurement, because the data were available as a file, rather than needing to be estimated by reading the plots from the spectrum analyser. Some information relating to the Ipswich measurements is noted in table 24 as 'unknown' because of inadequate record keeping at the time of the measurements.

Table 24: Ingress Noise Levels by Frequency Band

date	time	location	condition	frequency band (MHz)						Orwell
				1-4	4-7	7-10	11-14	14-17	17-20	
inknown	unknown	300m cable	noise floor test	-90	-90	-90	-90	-90	-90	-69
unknown	unknown	Church Close S/S	overhead system	-66	-73	-78	-74	-84	-100	-20
03/04/98	12:20	house A	PH	-75	-69	-69	-72	-75	-80	-53
25/03/98	15:30	house A	PH	-75	-64	-67	-67	-74	-84	
20/03/98	16:30	house A	supply side PH	-63	-54	-57	-67	-77	-85	
unknown	17:10	house A	PH	-46	-54	-54	-64	-77	-83	
21/03/98	17:50	house A	blue PH	-50	-58	-60	-75	-83	-88	-37
22/03/98	19:10	house A	PH	-54	-57	-61	-73	-80	-87	-35
23/03/98	19:25	house A	?	-53	-55	-60	-55			
20/03/98	20:00	house A	PH	-52	-49	-54	-70	-82	-88	-10
19/03/98	21:00	house A	PH/blue	-35	-37	-47	-55	-53	-58	
23/03/98	23:35	house A	PH	-57	-54	-65	-75	-82	-85	
unknown	unknown	house A	cumulative PH blue	-19	-25	-30	-35	-42	-48	
unknown	unknown	house B	?	-70	-73	-69	-92			
unknown	day	Landseer Rd S/S	-73	-73	-73	-73	-90	-90	-90	-61
25/03/1998	day	Lawns S/S	busbar	-80	-76	-72	-76	-82	-87	-48
25/03/98	19:25	link box B	?	-67	-61	-65	-90			
unknown	unknown	Link box B	?	-72	-83	-84	-90	-90	-90	
28/11/2003	12:21	Woolley Hall garage	socket outlet	-82.76	-95.35	-90.7	-97.52	-97.53	-98.65	n/a
03/12/2003	13:51	Elgin master	socket outlet	-84.43	-97.68	-97.02	-95.17	-96.38	-101.68	n/a
04/12/2003	10:07	Mycroft EAM	socket outlet	-86.21	-96.46	-95.67	-94.99	-96.19	-102.22	n/a
AVERAGES										
house A (day)				-71.0	-62.3	-64.3	-68.7	-75.3	-83.0	
house A (night)				-50.2	-51.7	-57.8	-67.2	-76.0	-81.2	
overall				-64.30	-66.40	-68.49	-76.08	-80.62	-85.86	

It should be noted that the levels shown in table 24 are expressed in dBm, not dB μ V as is more usual. The spectrum analyzer used had an input impedance of 50 Ω and was calibrated to convert the applied voltages to a power reading.

The measurements have been averaged across all sites and times, which provides an indication of which of the frequency bands are the quietest. The result of this averaging is shown in fig 64. The characteristics of the

ingress noise vary between day and night as radio users shift frequency to maintain service as the ionosphere changes. The difference between night and day for each frequency band as experienced at house A is shown in fig 65; this being an important consideration in the design of PLT systems because it means that in some bands the signal to noise ratio changes significantly over the diurnal cycle.

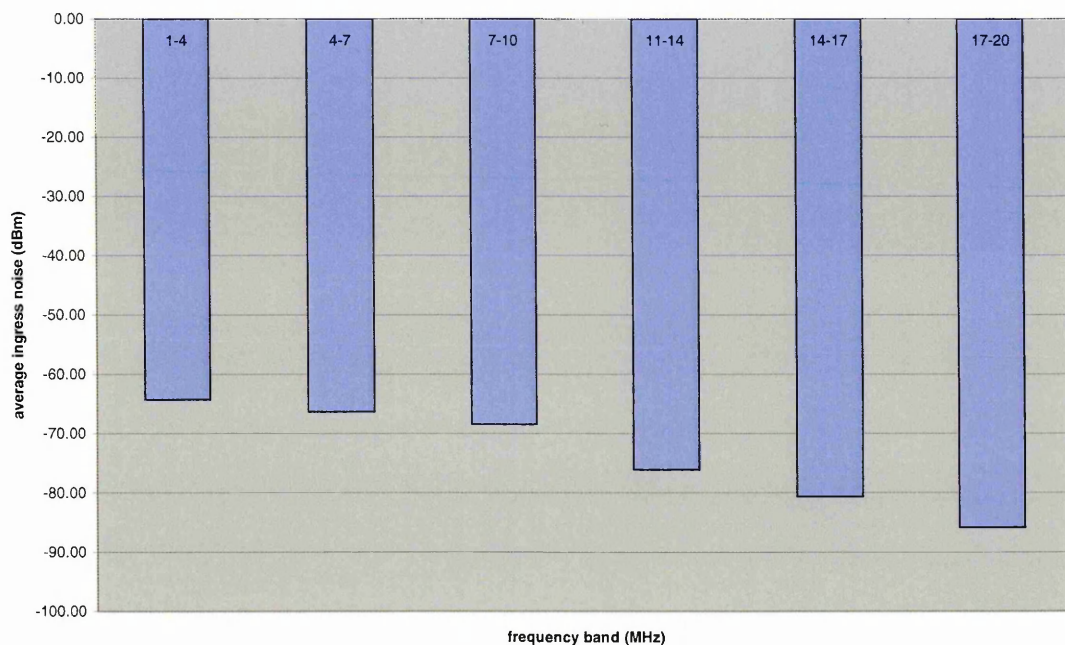


Figure 65: Average Ingress noise by frequency band; all sites and times

It can be seen from the graph that the higher frequency bands are quieter by some 20dB than the lower bands.

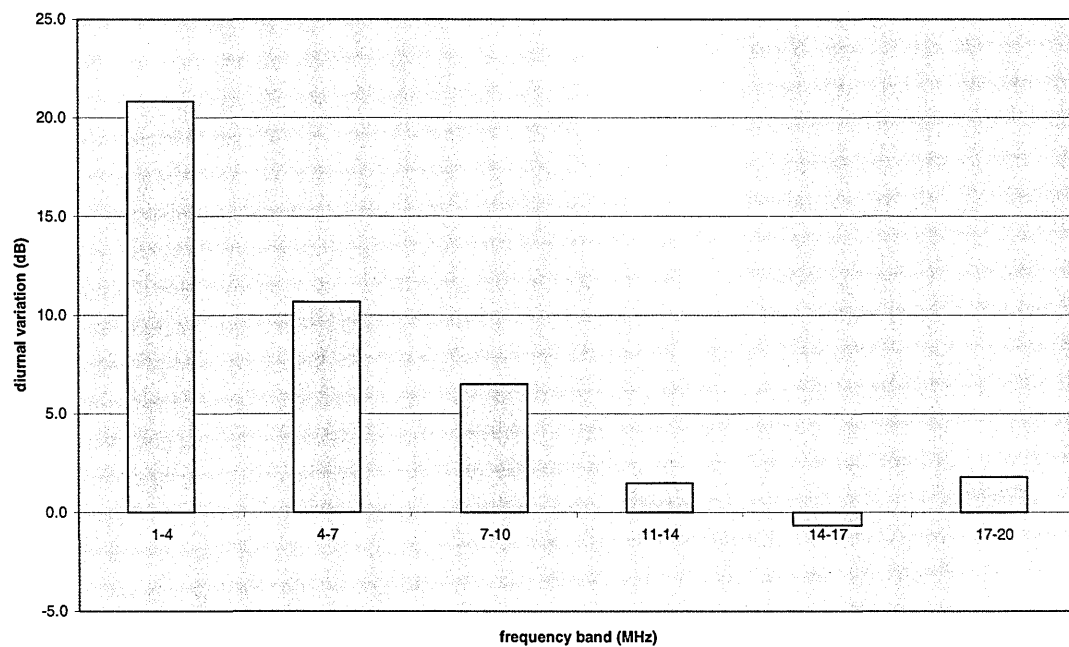


Figure 66: Diurnal variation of ingress level by frequency bands

Fig 65 shows that in addition to being quieter than the lower frequency bands, the bands above 10MHz also have less variation of ingress noise between night and day than do the lower bands.

8.2.8. Transient Noise

Transient noise measurements were made in two ways:

- With the BMI Powervista 100G Power Quality Monitor
- With the W&G GM1 noise meter.

The BMI instrument is intended for establishing the quality of the mains power supply and is insensitive in communications terms but can run unattended for long periods of time. It was therefore used to establish the long-term trends in terms of transient noise.

8.2.8.1. Results using the Power Quality Monitor

The BMI Powervista 100G Power Quality Monitor (PQM) was left in operation for 8 days, starting from Wednesday 25 March 1998. During that period, a total of 132 significant events were recorded, which were clustered into 31 incidents. These were counted manually from the printouts from the PQM, which produced a paper record each time something happened that was outside the set limits. The parameters used for determining an event that would be significant in communications terms were as follows:

- only Line to Neutral voltages were counted (the PQM also records Neutral to Ground voltages)
- both HF bursts and voltage spikes were counted

The HF noise threshold was 15V peak and the L-N impulse threshold was 400V peak, these being a function of the instrument.

The PQM provides a graphical representation of each disturbance, enabling the duration of an HF burst and the position of a transient in the mains cycle to be estimated. A representative sample is shown in figs 67 to 70, which are scans of the paper records from the PQM.

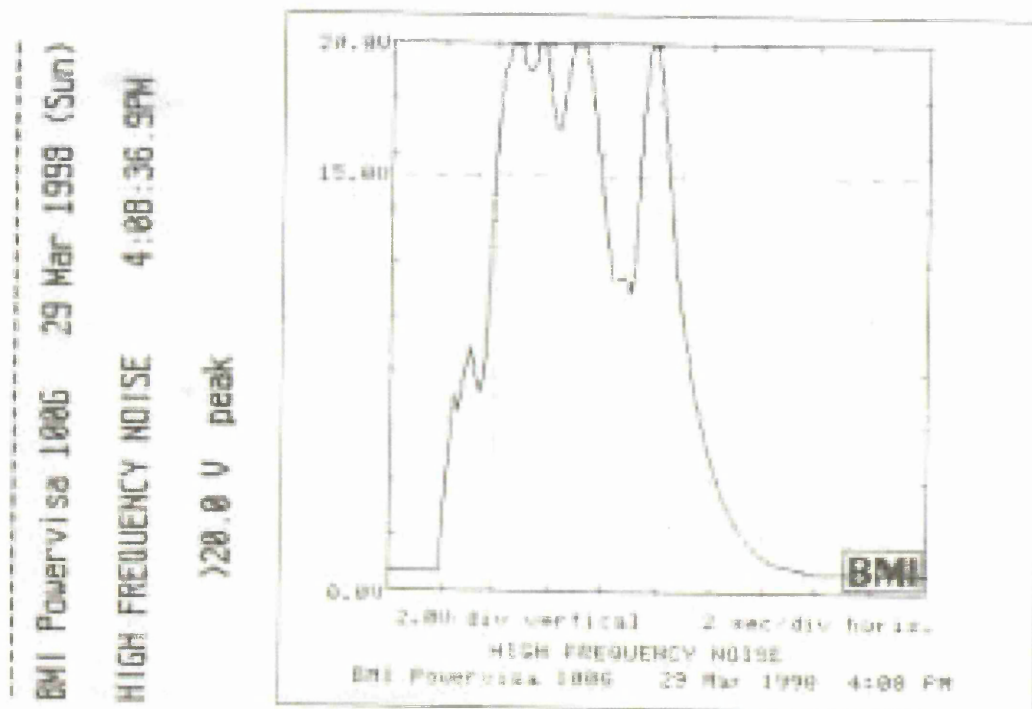


Figure 67: Twelve second HF noise burst

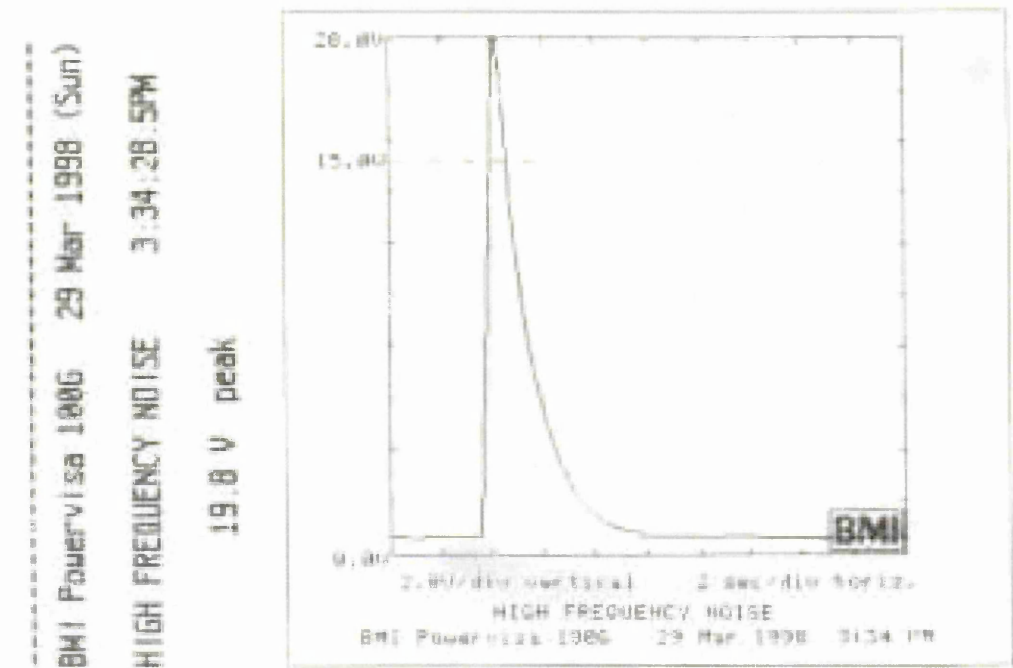


Figure 68: Five second HF noise burst

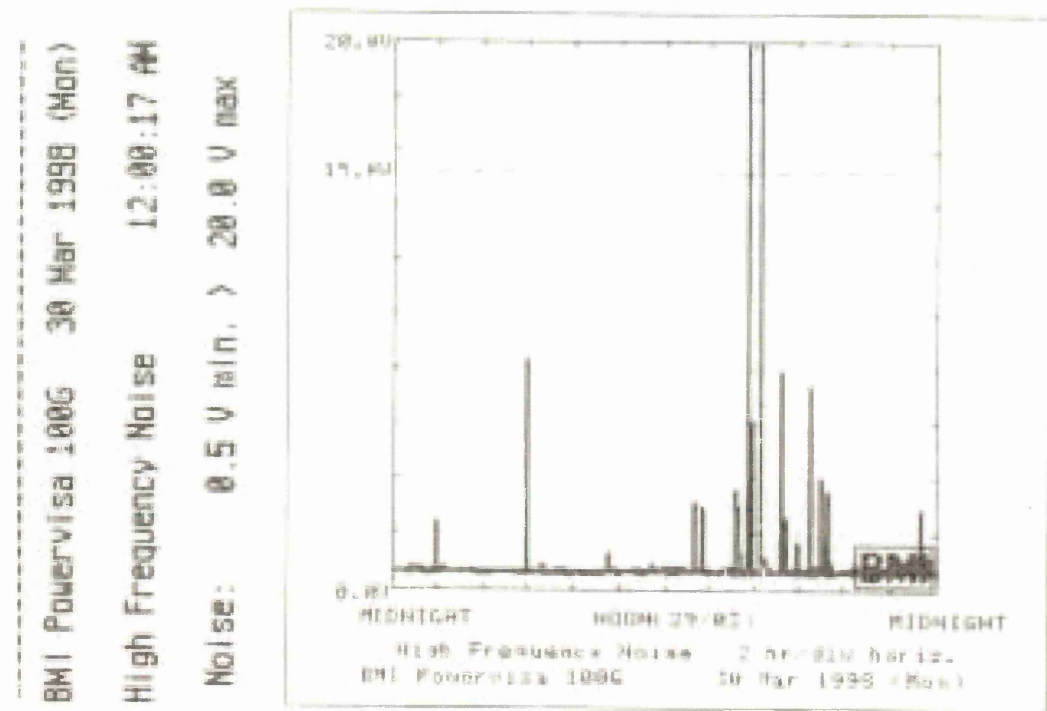


Figure 69: Cluster of HF Noise Impulses

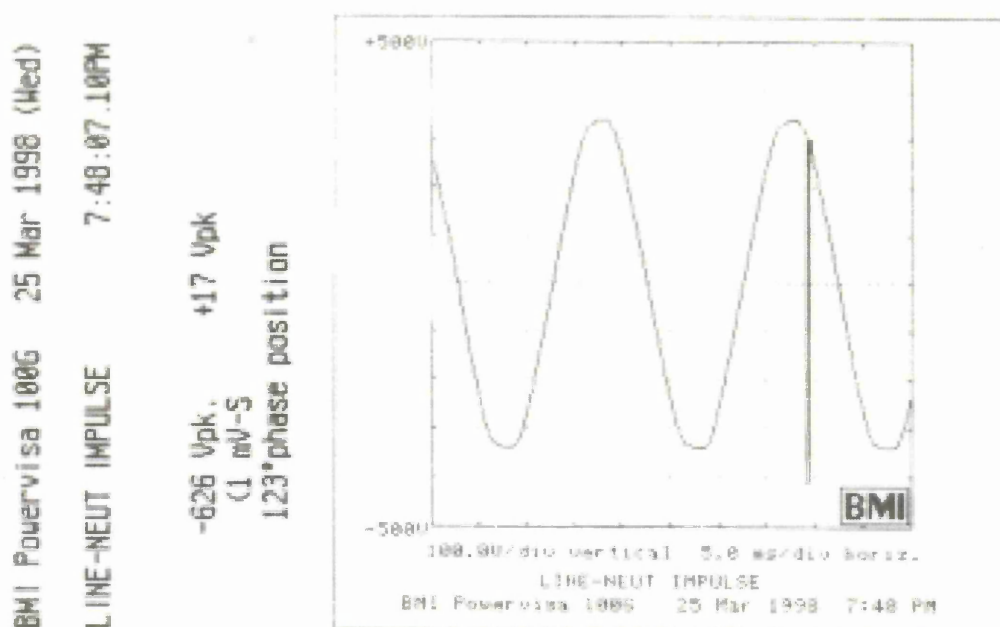


Figure 70: Isolated noise impulse, showing position in power waveform cycle

Transient noise of the type shown in figs 67 to 70 will have a significant effect on power line communications, because of both its magnitude and duration. An analysis of the 8 days of recording provides the following information:

Total transients: 132
 Total events¹²: 31
 Total time recorded 192 hours

From this, it can be deduced that there is a 16% probability of an event occurring in any hour, and that

¹² where and 'event' is defined as a time period that may contain a cluster of transients, as shown in fig 24

the average number of transients in one event is 4.3. The worst recorded event was the 20.8V peak burst of HF lasting 12 seconds, shown in fig 67.

8.2.8.1.1. Results Using the Noise Meter

Recordings were made with the noise meter throughout Sunday 26 January 2003. The number of transients per hour were recorded, the counters and timer being reset each time a reading was taken. The results are shown graphically in fig 71.

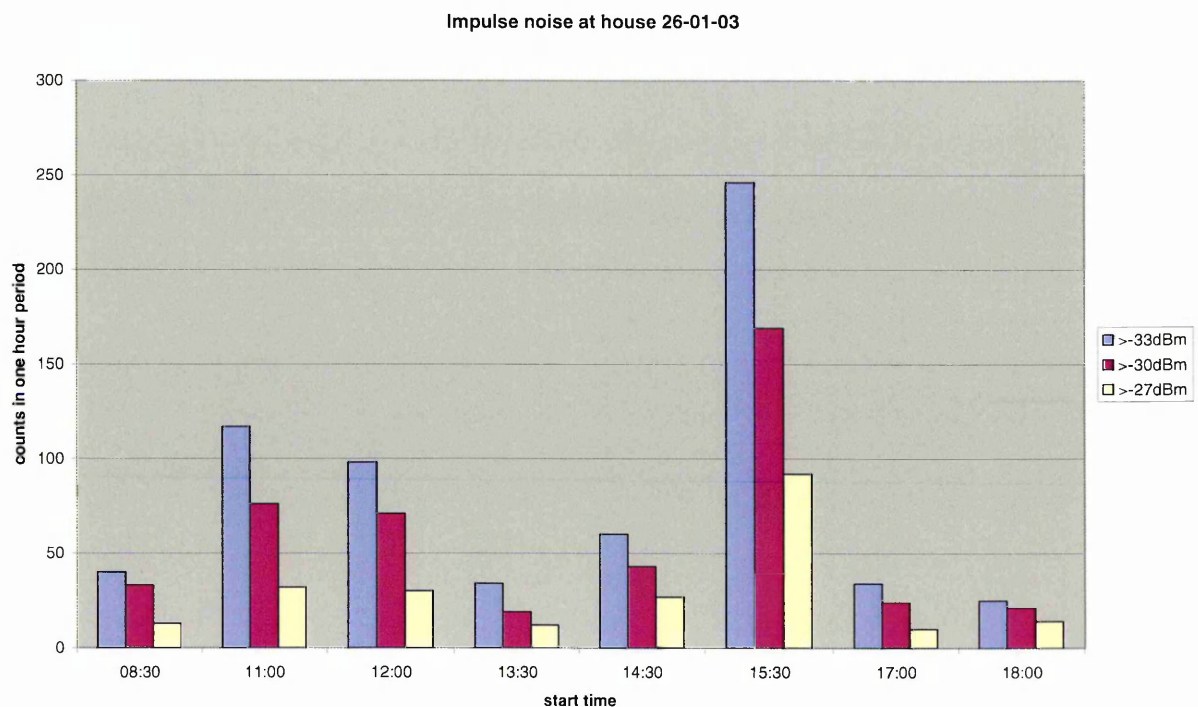


Figure 71: Incidence of transients

Figure 71 shows that there are considerably more transients at a level that would affect powerline

communications than would be expected from the analysis of high-level transients provided by the power quality monitor. The signal levels on the graph are expressed in dBm because that is how the instrument was calibrated. The instrument was connected in bridging mode, with an input impedance of 20k Ω , so the voltages relating to each of the levels shown on the graph can be calculated as shown in equation 29.

Equation 29: relationship of transient voltage to measured power

$$V = 20 \times \log(10^6 \times \sqrt{10^{(p-30)/10}} \times 20000)$$

where V is the voltage (dB μ V) and p is the power measured (dBm).

This gives the levels on the graph as:

Level in dBm	Level in dB μ V
-33	100
-30	103
-27	106

The graph does not show the complete story about the distribution of noise impulses because they are averaged over one hour periods. The noise meter was observed occasionally during the day and it was noticed, as suggested by the PQM prints, that transients tended to

occur in bursts; for example some 5 minutes into the 11:00 test a burst occurred that took the reading to 66% of the total for that hour. As the meter uses mechanical counters the activity was experienced as the sound of the counters 'motoring' as the impulses arrived in rapid succession.

Unfortunately, no equipment was available that could determine the duration of these low-level impulses.

8.2.8.1.2. Results from Other Studies

Some information on the incidence and duration of transients is given in an ERA report [ERA 1988, table 1]. This has been simplified for ease of use in the context of this thesis and is shown in table 25. The original table split the information by transient amplitude but because all the amplitudes were significant in telecommunications terms table 25 shows the totals that exceed a given duration. All the transients exceeded 50V and are therefore significant in communications terms. It is to be noted that none of the transients recorded by ERA were the result of lightning activity and that only negative going transients were recorded. The numbers in the table represent the average number of 'spikes' (sic) per day and are said to be the result of switching of appliances and to be applied in both differential and

common modes. The ERA took measurements at domestic premises fed by both underground and overhead networks, at a London Electricity Board substation, at their own substation and at an unspecified industrial site.

Table 25: Average number of spikes per day from ERA report

location	Duration exceeded (μs)			
	0.1	1	10	100
Domestic u/g fed	240	174	65	0.5
Domestic o/h fed	394	394	94	1.1
ERA substation	216	65	2.9	0.22
LEB substation	12.8	12.8	10	0.62
industrial	4470	3280	2630	1

The original data show that the transient voltages were higher at the overhead fed house than at the house fed by an underground cable. It should be noted that the table is cumulative, so that the column representing spikes exceeding $0.1\mu\text{s}$ duration includes the figures for spikes of longer duration.

8.3. Review of the Measurements

The measurement programme was intended to provide the information necessary for the use of the mathematical models, and to assess the operation of the trial systems in comparison with the proposed standards and the potential radio interference. The main conclusions from the two aspects of the measurement programme are as follows.

8.3.1. Trial systems

The measurements on trial systems provided the following information:

- all systems tested exceeded the CISPR 22 conducted limits, including the proposed multipurpose limits
- all systems tested exceeded the MPT1570 emission limits and the expected radio service signal levels
- even if a PLT system conformed to the CISPR 22 conducted limits its emissions could still exceed MPT1570 limits and thus it would be capable of causing radio interference, the conducted limit being set too high for MPT1570 conformance by at least 27dB (in the case of a mains port type B)
- a threshold test showed that at least one system was set to a power injection in excess of what was

required to achieve error-free communications under all conditions of operation

- the systems tested did not conform to the ETSI TS 101 869 in-house/access coexistence band plan
- the in-house system tested had the potential to cause interference to access systems used in other premises some distance from the in-house system.

It was noted that the emissions from PLT tended to raise the level of the carriers of broadcast stations, which sat on the noise floor caused by the PLT system.

Although this appears to leave the broadcast signal an acceptable signal to noise ratio for good reception that is not the case; the PLT signal is modulated and subject to TDM switching, which causes the level of the broadcast signal to be amplitude modulated by the PLT signal, resulting in audible interference.

8.3.2. Clean Distribution Networks

The measurements on networks without PLT provided information for the mathematical models in the following areas.

- attenuation per unit distance of a number of different types of underground distribution system cable, analysed into 3MHz wide sub-bands. This

showed that the mean loss, averaged over all sites and all frequencies, was 44dB/100m

- attenuation per unit distance for a UK LV overhead distribution network, analysed into 3MHz wide sub-bands
- values of ingress noise, analysed in 3MHz wide sub-bands
- values of k factor for a number of buildings and items of illuminated street furniture, analysed into 3MHz wide sub-bands
- values of k factor for an overhead network, analysed into 3MHz sub-bands
- values for the inter-network isolation across an open link box, analysed into 3MHz wide frequency sub-bands, showing that the isolation between different LV networks is so low that problems may be encountered in operation at the ends of adjacent networks where they meet in a link box
- values for the phase coupling loss (near end and far end) on a LV underground distribution cable, analysed into 3MHz wide sub-bands, showing that the isolation is insufficient to permit the operation of different data streams on different phases

8.4. Summary

This chapter has provided information on the results of the measurement programme and quantification of the major parameters affecting PLT transmission. The next chapter illustrates how these parameters can be used to determine the theoretical transmission capacity of a PLT hop under the MPT1570 emission limits, and how the performance of the system can be optimised within the emission limits by utilising the available frequency spectrum correctly. It then shows how the resulting band plan would be utilised in a LV distribution network.

9. BAND PLANNING FOR PLT SYSTEMS

The previous chapters have presented an evaluation of the attenuation, noise and emission characteristics of two typical LV networks, and the mathematical tools needed to relate these characteristics to the data transmission capacity of a PLT system. In order to define the radio spectrum requirements of PLT it is necessary to formulate a band plan, defining the most effective way of assigning frequencies for the various services that might be carried. At present, the only guidance available to prospective PLT equipment manufacturers is the ETSI in-house/access co-existence standard [ETSI 2000] that assigns the frequency band 1.6MHz to 10MHz to access systems¹³ and 10MHz to 30MHz for indoor applications¹⁴. This chapter examines the basic parameters of the physical medium to establish the optimum use of the radio spectrum to maximize the performance potential of PLT. A prediction of the performance that should be obtainable is made in this chapter.

¹³ systems running on the distribution mains to provide residential broadband services

¹⁴ services running on private wiring, such as private LANs, telephone extension or video distribution (VCR extensions)

9.1. The Near/Far Problem

A problem that is basic to all telecommunications systems that provide multiple occupancy is that of preventing or ameliorating the effects of mutual interference between users. Two commonly used methods of doing this are Frequency Division Multiplexing (FDM) and Time Division Multiplexing (TDM). In FDM, different users are assigned separate frequencies while in TDM they use the same frequencies but are assigned different time slots, normally controlled by synchronisation signals from the master controller of the network. The near/far problem refers to the blocking effect of a local transmitter on a nearby station that is attempting to receive a distant signal; a problem that is " particularly severe in the case of direct sequence [spread spectrum] systems.." [Cooper and McGillem 1986 pp279] but can affect any type of communications technology. Because of the way in which LV substations are interlinked, this problem requires careful consideration in PLT access systems.

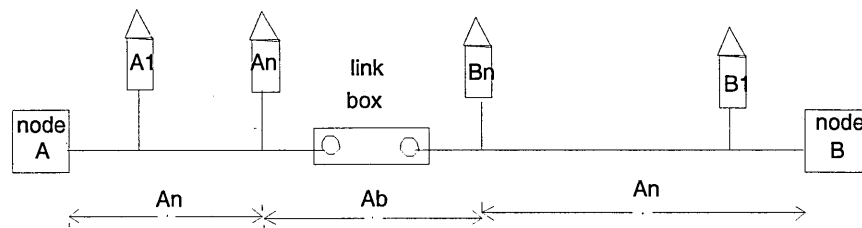


Figure 72: The near/far problem

Fig 71 shows a section of network consisting of an interconnector between two substations containing PLT node equipment; node A and node B. Under fault conditions, the link box allows the feed from substation A to be restored from substation B by inserting the links, which are normally left out. A1 and B1 are the houses closest to their respective feed points, while houses An and Bn are the houses on the substation A and substation B sides respectively that are closest to the link box.

The network attenuation between the substation and the link box on each side of the box is A_n dB. The attenuation across the box in the normal running condition with the links open is A_b dB. The following assumptions are made:

- All houses have the same k factor
- The attenuation between the node equipment and the first house is the same for the A and B sides
- A_n is the same on the A and B sides
- The transmission path between the node and the house is reciprocal (ie the upstream and downstream loss is the same).

Given the above conditions, the houses will receive the same signal level from their respective nodes and will use the same transmit power for upstream transmissions. Considering the case of house A_n , closest to the link box, equation 30 will apply.

Equation 30: Wanted power at a subscriber modem (A side)

$$P_{\text{wanted}} = P_t - A_n$$

Where P_{wanted} is the received signal level at house A_n from node A, A_n is the attenuation between house A_n and its home node and P_t is the power transmitted by the node. The same equation applies on the B side.

At the house A_n , the unwanted power is given by equation 31.

Equation 31: Unwanted power at a subscriber modem at house A_n

$$P_{\text{unwanted}} = P_t - A_b$$

Where P_{unwanted} is the signal at house A_n from house B_n , which is transmitting upstream data.

Combining equations 30 and 31, it can be seen that the wanted to unwanted signal to noise ratio in dB is given by equation 32:

Equation 32: Wanted to unwanted signal to noise ratio

$$SNR = Ab - An$$

Using the actual results, house A on the tested network is close to a link box, at the limit of the feed from The Lawns substation under normal conditions. By substituting values from the network attenuation measurements, the wanted to unwanted ratios shown in table 26 can be determined.

Table 26: Wanted to unwanted signal ratio for the tested network

Band (MHz)	Wanted to unwanted signal ratio (dB)
1 - 4	-34.82
4 - 7	-47.09
7 - 10	-59.83

In the table, the negative wanted to unwanted signal ratios indicate that the unwanted upstream signal from the house at the other side of the link box is stronger than the wanted downstream signal, which is a consequence of the loss across the link box being lower than the loss

from the house to its node. It can be seen that it is not possible for houses either side of the link box to operate simultaneously in different directions of transmission on the same frequencies. Given a mean mains attenuation of 44dB/100m [section 8.3.2] it can be seen that the wanted/unwanted signal to noise ratio would not be positive for some 100m on the far side of the link box from the upstream transmitter. Because it is unlikely to be possible to synchronise the polling on separate nodes so that houses on adjacent networks are protected by TDM this means that the same carrier frequency cannot be used at adjacent substations, thus reducing the bandwidth available. It must also be remembered that there is no isolation between the feeders connected to the same busbars and that different feeders may interconnect to more than one other substation.

This problem potentially exists between adjacent houses on a feeder but is managed by the polling protocol, which does not permit subscriber modems to go into transmission mode during a downstream transmission. The need for TDM to prevent simultaneous upstream and downstream transmission places a further limitation on the available data capacity.

There are two possible solutions to the problem between substations:

- Avoid the use of the same frequencies on adjacent substations. This is only possible on systems which use defined carriers, such as those using PSK, FSK or similar types of modulation.
- For wideband modulation systems (eg OFDM, direct sequence spread spectrum) the most practical solution is to use a band plan that divides the access band into downstream and upstream sub-bands. Most of the services likely to be carried by a PLT system would not require equal bandwidths for upstream and downstream operation, as most upstream traffic consists of requests for data, with an occasional data upload. This is analogous to the operation of ADSL.

The simplest solution to the near/far problem is to assign separate bands for upstream and downstream operation, thus facilitating frequency re-use on adjacent substations. Given a worst-case (ie least) loss across a link box of 16dB¹⁵ and using the assumptions made in the above calculation, it should still be possible to achieve 16dB of wanted to unwanted signal to noise ratio (protection ratio) at the node even if the same upstream carrier frequency is used on either side of an open link

¹⁵ 4-7MHz band value from table 15

box. The use of separate upstream and downstream bands will also simplify the use of repeaters. Only one of the trial systems on which measurements were made used band assignments of this type.

Consideration of the best way of selecting the upstream and downstream bands must await more information on the data capacity of PLT systems later in this thesis.

9.2.Signal to Noise Ratio Available in 3MHz Sub-bands

As an introduction to the section on estimating the data capacity of PLT systems, a graph showing the signal to noise ratio for downstream transmission on an underground system has been prepared. This is based on the downstream link power budget model [equation 3]. For each 3MHz sub-band the mean attenuation of all the various underground cables that were measured has been used, together with the mean day and night ingress figures for the house with the highest ingress noise. A hop length of 100m and a modem transmit power of 0dBm are assumed¹⁶. The results are shown graphically in fig 73 and in tabular form with the source data used in this chapter as table 27.

¹⁶ In practice, this power would be far too high but is convenient for the purposes of comparison

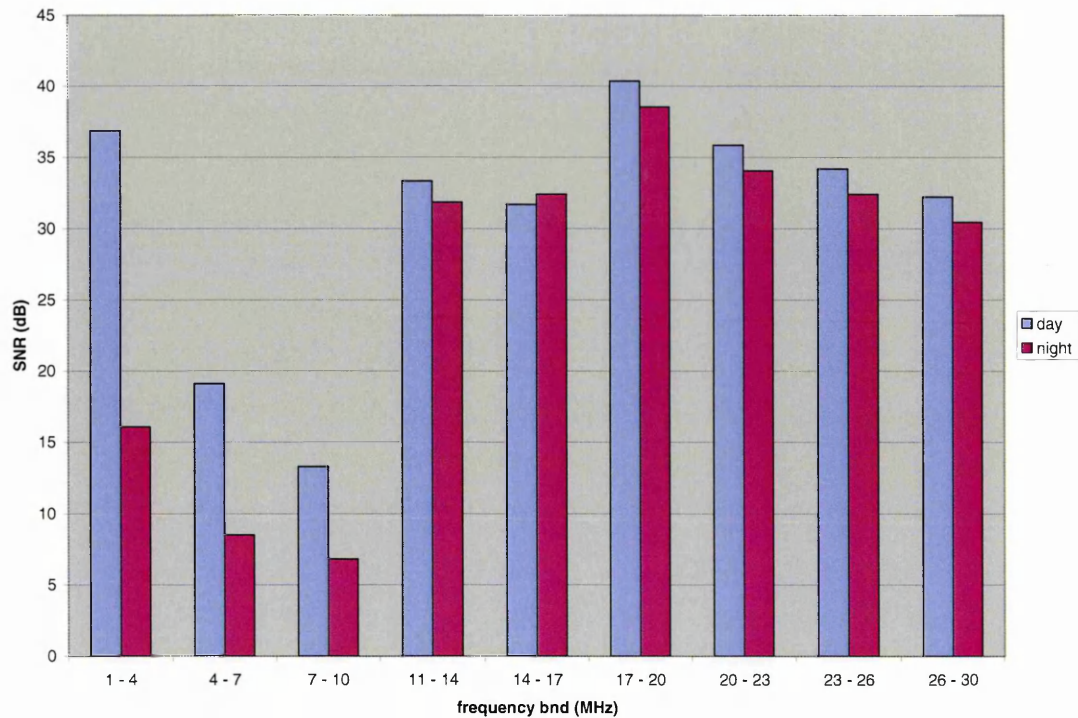


Figure 73 Signal to noise ratio by sub-band at 100m with 0dBm TX

Table 27 Average Cable loss and Ingress noise for underground network capacity assessment

route	loss/100m by frequency bands (dB)								
	1 - 4	4 - 7	7 - 10	11 - 14	14 - 17	17 - 20	20 - 23	23 - 26	26 - 30
house A to link box A	32.5	36.2	44.1	38	52.1	51.8	61.3	65.2	67.3
house A to Lawns	22.7	26.4	33.2	32.7	35.1	33.5	33	32.4	34.2
link box A to Lawns (PILC)	27.3	36.5	37.9	not measured					
link box A to Lawns (plastic)	30.5	40.5	54.6						
house B to Lawns	57.53	76.38	85.18						
mean loss (dB/100m)	34.11	43.2	51	35.35	43.6	42.65	47.15	48.8	50.75
mean ingress (dBm) at house									
day	-71	-62.3	-64.3	-68.7	-75.3	-83	-83	-83	-83
night	-50.2	-51.7	-57.8	-67.2	-76	-81.2	-81.2	-81.2	-81.2
day/night correction (PSCRG)	4.19	7.24	4.1	-1.77	-3.94	-2.59	-4.85	-2.73	0.04
noise at link box (dBm)									
day	-72	-83	-84	-90	-90	-90			
night (using correction factor)	-67.81	-75.76	-79.9	-91.77	-93.94	-92.59			
noise at busbars (dBm)									
measured day	-80	-76	-72	-76	-82	-87			
night (using correction factor)	-75.81	-68.76	-67.9	-77.77	-85.94	-89.59			
SNR at 100m for 0dBm TX (based on house ingress)									
day	36.89	19.1	13.3	33.35	31.7	40.35	35.85	34.2	32.25
night	16.09	8.5	6.8	31.85	32.4	38.55	34.05	32.4	30.45

Table 27 shows how the mean cable loss is derived from the measurements detailed in chapter 8. The mean ingress

noise is taken from table 24. Because of safety considerations, full ingress noise measurements were not made on live conductors at the substation or link box after dark. The daytime ingress noise figures for the substation and link box were therefore converted to an estimate of the night ingress by using correction factors established from measurements of the broadcast background noise by the PSCRG [PSCRG June 2004]. The calculated signal to noise values for 0dBm transmit power shown in the table are plotted as fig 73, which is included only to illustrate the differences in available signal to noise ratio in the various sub-bands for an arbitrary level of modem injection power. Other factors determine the usable injection power setting and are included in the capacity calculations that follow. Fig 73 illustrates clearly that the lower frequency bands have a greater diurnal variation in signal to noise ratio than the bands above 10MHz. More significantly, the lower frequency bands have a poorer signal to noise ratio than the higher frequency bands, despite the increased cable attenuation of the latter. It can thus be seen that the ETSI in-house/access compatibility band plan [ETSI 2000] is flawed, in that it designates the 'best' bands for in-house operation.

9.3. An Estimate of the Data Capacity of PLT Systems

Estimates of PLT capacity have been made using the data presented in chapter 8. The main emphasis of the study is for PLT operating on underground networks, using the cable attenuation and ingress noise figures shown in table 27. Capacities are calculated for the nominal 3MHz analysis frequency bands in which the results are presented. For the capacity calculations the MPT1570 emission limits at the centre frequency of each of the 3MHz analysis bands were used to determine the modem injection power for the signal to noise ratio calculation, rather than the arbitrary 0dBm injection used to illustrate the difference in signal to noise ratio in fig 73. The k factors used to calculate the injection powers were as measured at the detached house with an underground service (house A), as shown in table 22. The capacity calculations used equation 3 for the downstream signal to noise ratio and equation 4 for the upstream signal to noise ratio in each 3MHz analysis band. Having determined the signal to noise ratio, the data capacity of the band was calculated by using the Shannon equation [equation 13], with the bandwidth set to 3MHz. The results are shown for both directions of transmission and for distances of up to 140m. Although this does not cover the full distance required the extra reach necessary can be achieved using repeaters and this

method of operation is a feature of the trial systems that have been seen [PSCRG 2004].

9.3.1. Overhead Network

An estimate of the capacity of the overhead network was made on the basis that the mains are the principal source of emissions. The results of the capacity calculations using the MPT1570 emission limits are shown in fig 74. The capacity calculations are based on the k factors of the Rushmere Church overhead line and the ingress noise levels measured at the Church Close substation busbars.

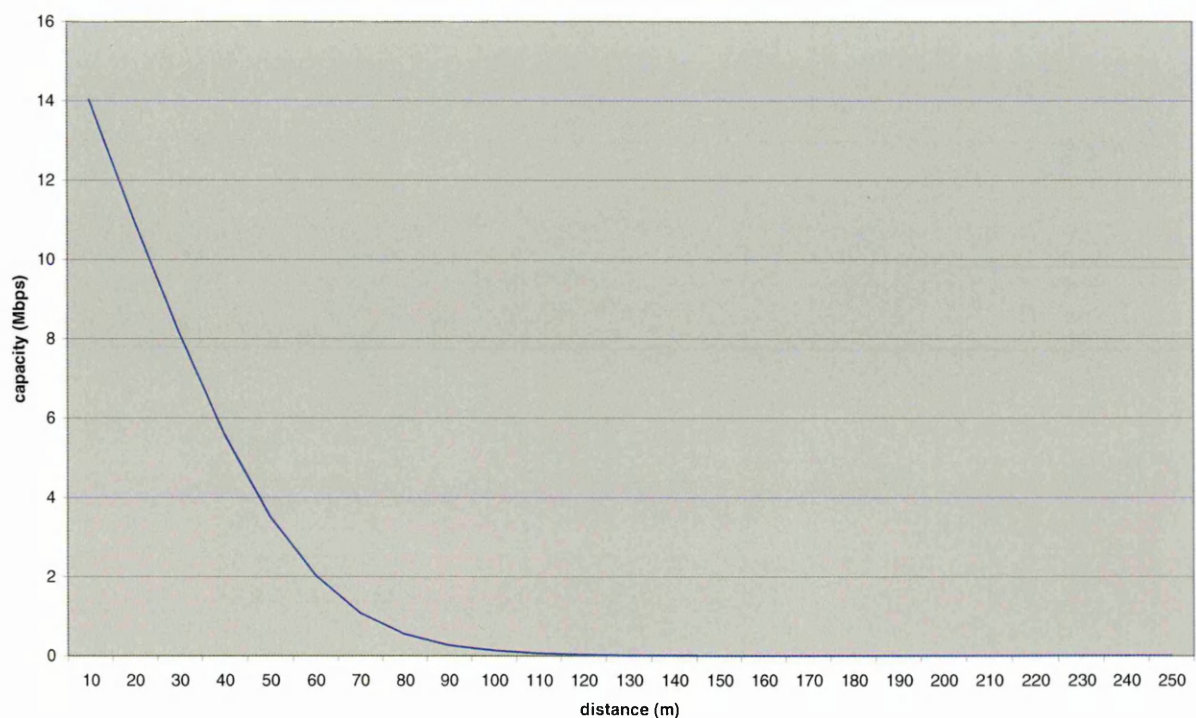


Figure 74 Estimated capacity of overhead network in 1 - 4MHz band under MPT1570 Limits

Fig 74 shows that the capacity is quite low, falling to around 1Mbps at 70m range. By increasing the emissions above the MPT1570 limit the capacity can be increased as shown in fig 75.

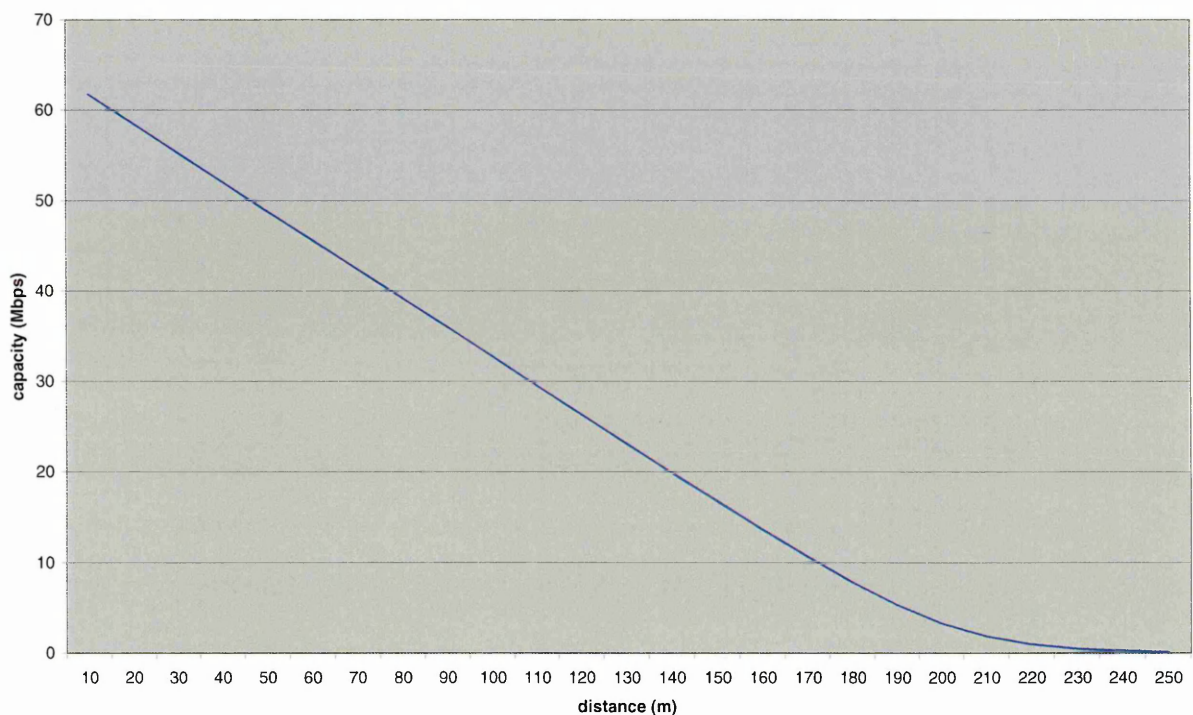


Figure 75: Estimated capacity of overhead network in 1 - 4MHz band with increased emissions

The graph of fig 75 was plotted on the basis of the emission level needed to increase the capacity at 60m range to approximately 45Mbps in the 1MHz to 4MHz sub-band. The required emission level was 65dBuV/m for a capacity of 45.66Mbps. This result is confirmed by measurements undertaken by the Open University Power Systems Communications Research group in Australia, where

a 45Mbps system was producing emissions of around 70dB μ V/m under the line close to the repeater [PSCRG 2005 pp29].

An alternative way of comparing the prediction against the Australian system is to use the emission factor concept proposed in section 5.4 of this thesis. From the results for the Australian system, which used repeaters spaced at 60m, the mean emission from two of the repeaters in the 1 - 4 MHz band was 65dB μ V/m. The emission factor for the Australian system was therefore given by equation 33, which is based on equation 15.

Equation 33: emission factor at Bruce St master

$$EF = 65 - 10\log(45000) - 10\log(60/1000) = 30.67dB\mu V / m$$

The emission factor for the theoretical performance, based on the Ipswich overhead network is given by equation 34.

Equation 34: emission factor for theoretical Ipswich system

$$EF = 65 - 10\log(45.66 \times 10^3) - 10\log(60/1000) = 36.21dB\mu V / m .$$

In equations 33 and 34 the LCL has been omitted because in Australia it was not possible to shut down the PLT system to facilitate LCL measurement. Safety considerations relating to overhead line systems also made LCL measurements impractical on both systems. However, given the differences in construction between

the two mains networks this result appears to support both the emission factor concept and the capacity calculations, as the difference of only 6dB is small in the context of the unknown factors resulting from the limitations of the measurements.

The results for the overhead system suggest that, given that the average number of customers passed is 50 and the takeup rate is 13%, broadband PLT via overhead mains is unlikely to be acceptable in the UK from either an economic or a radio interference viewpoint, and so this study has focused on underground LV distribution systems.

9.3.2. Underground Network

This section explores in detail the potential performance of the underground network in both the downstream (node to customer) and upstream (customer to node) directions.

9.3.2.1. Downstream Capacity

An initial evaluation of downstream capacity was made for systems required to meet the MPT1570 limits. Fig 77 shows the downstream capacity for daytime levels of ingress and fig 78 shows the night-time capacity, based on the use of fixed transmitter power. For these

calculations, the transmission power is set by the house closest to the substation, which is assumed to have k factors as house A and to be located 20m from the substation. The ingress noise figure used for this calculation is that measured at the house A on the Ipswich underground network.

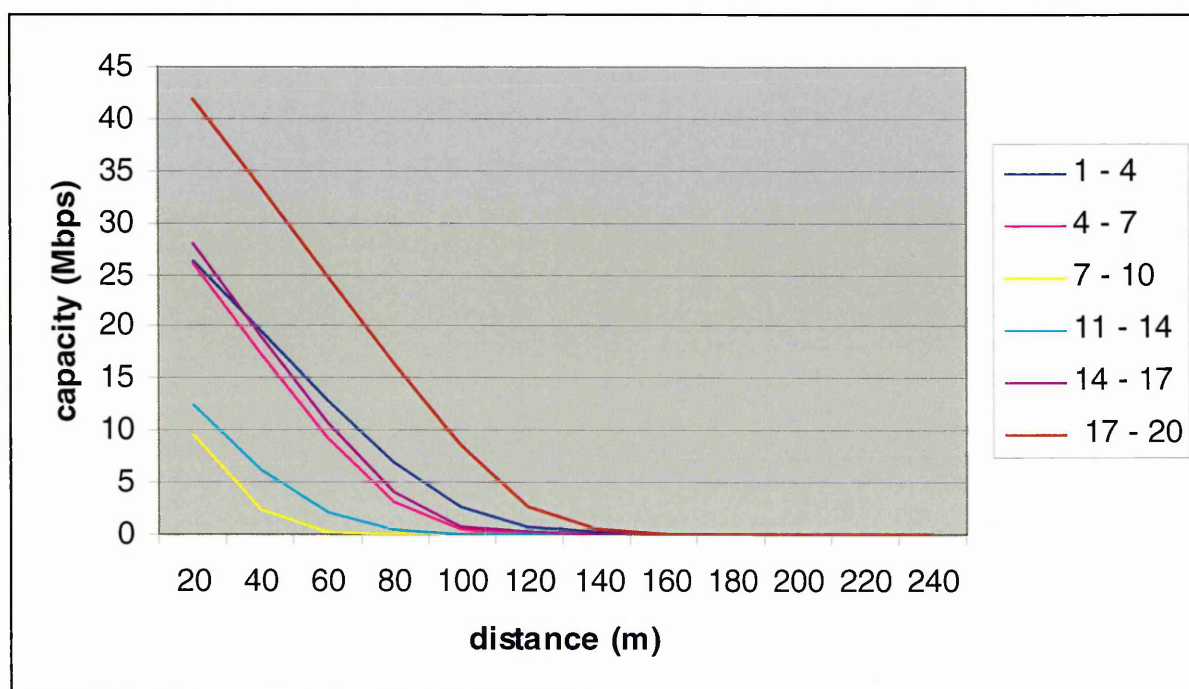


Figure 76: Daytime downstream capacity

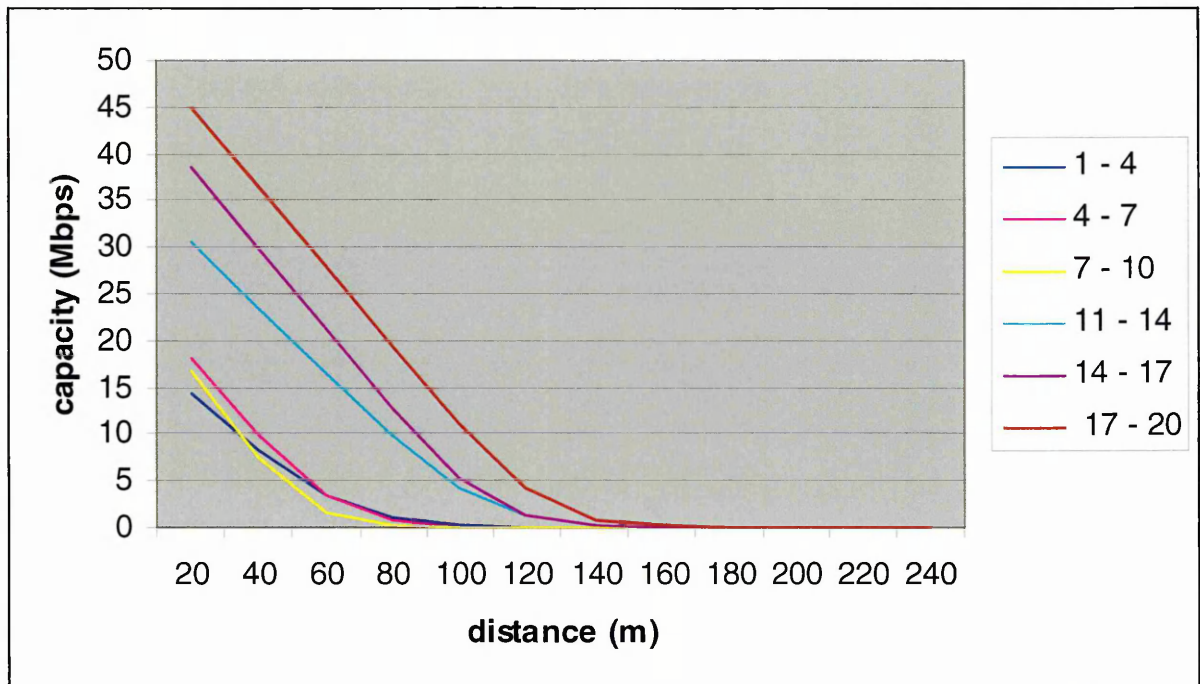


Figure 77: Night-time downstream capacity

Any broadband service must deliver the specified capacity regardless of changes in operating conditions. From figs 76 and 77 it can be shown that the best performing bands in terms of data capacity throughout the diurnal cycle are the bands above 10MHz, which suffer lower ingress noise and diurnal variations in capacity. The graphs also show that the maximum hop length cannot realistically exceed 100m if useful data rates are to be achieved. Not only does this mean that the bands above 10MHz could offer useful access band capacity for subscribers close to the node, but also that the risk of interference between in-house systems using the ETSI band plan [ETSI 2000] in different buildings is real, posing potentially awkward problems for power companies to resolve if in-house PLT ever became popular.

One possibility is that PLT systems will use an incoming filter [fig 16] in a service taking premises to enable a higher modem power to be used for upstream transmission within an emission limit. The use of such a filter will also enhance the downstream data capacity, by reducing the ingress noise injected by the local wiring of the premises using the system. Fig 78 shows the data capacity available if such a filter is used. Here it is assumed that a 60dB filter would be fitted, but as that would result in a local ingress noise injection well below the noise measured on the network, the network noise measured at a link box is used as a good approximation to the level that would be received from the network at a house.

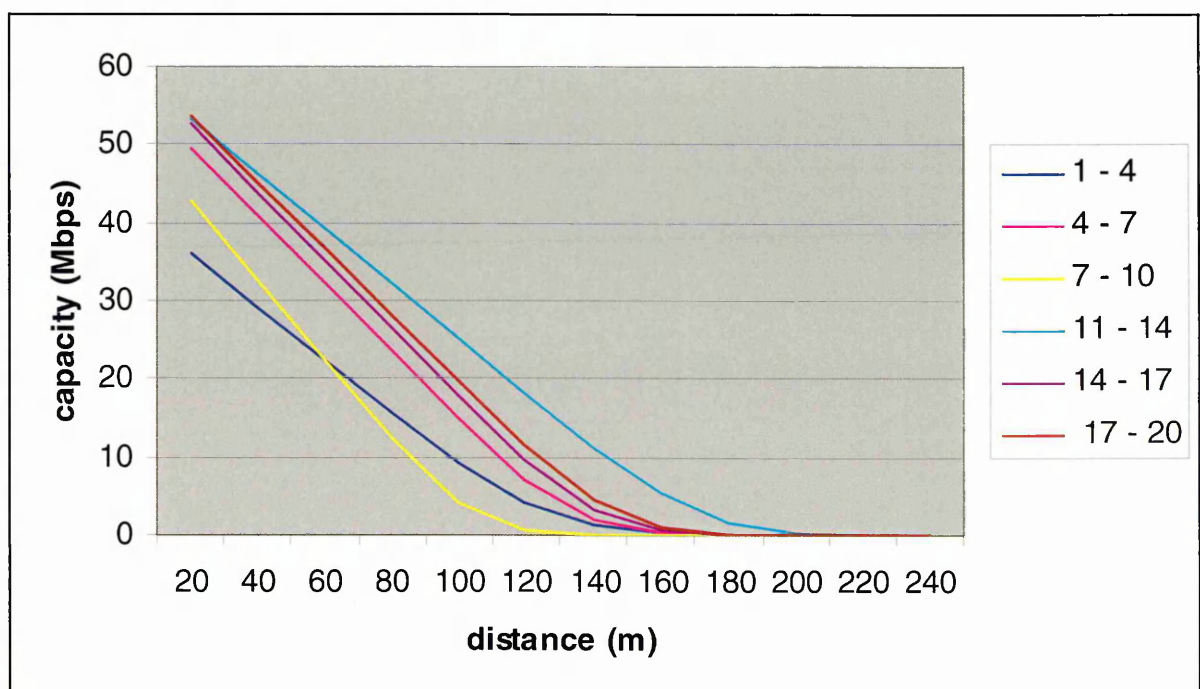


Figure 78: Filtered downstream daytime capacity

It can be seen from fig 78 that the action of fitting an incoming filter at a subscriber point has a dramatic effect on the downstream capacity; for example, increasing the capacity of the 4MHz to 7MHz band at 140m from 0.15Mbps to 1.99Mbps, without increasing the emissions by raising the transmitter power. It should also be noted that the distance limit for the 11MHz to 14MHz band has now doubled to 240m from the unfiltered daytime value of 120m, although the data rate available at this distance is only about 20kbps.

The effect of the incoming filter on the night downstream capacity is shown in fig 79.

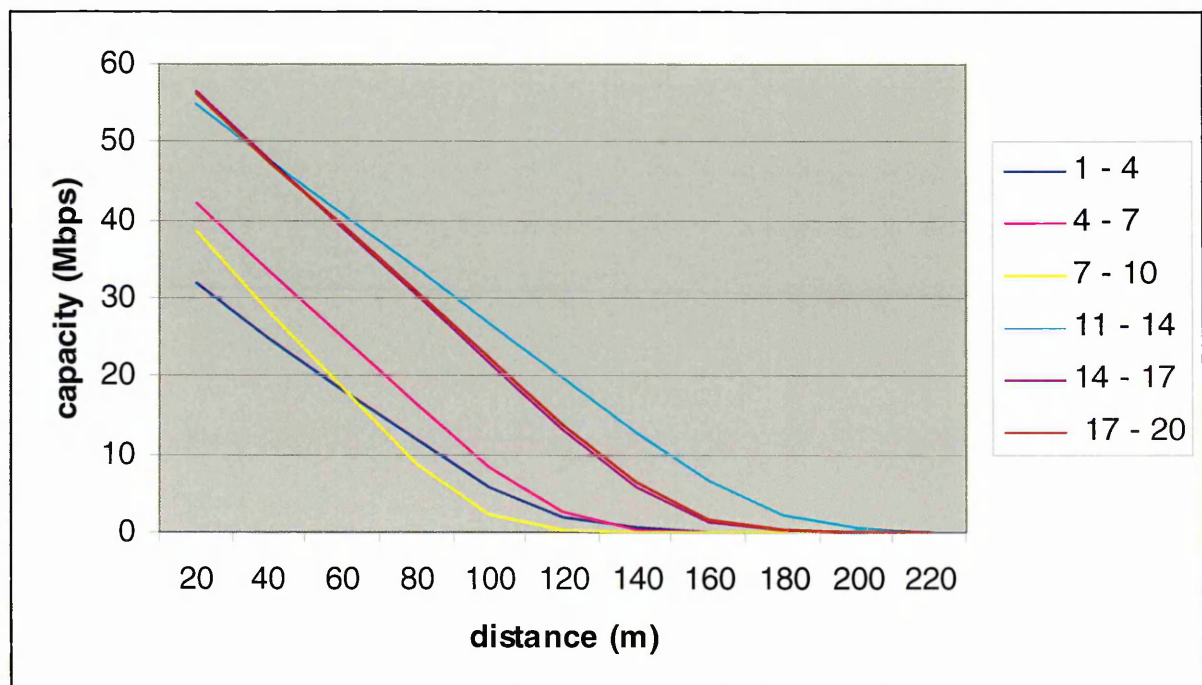


Figure 79: Filtered downstream night capacity

9.3.2.2. *Upstream Capacity*

The upstream capacity is hindered by the fact that a radiating structure - the wiring of the building in which the modem is located - is connected directly to the modem terminals with negligible network loss. It is thus attractive to fit an incoming filter, as already described [fig 16], between the incoming service cable and the building installation, with the access modem connected to the supply side of the filter.

Unfortunately, although suitable filters with an attenuation of 60dB can be purchased, it is not possible to increase the modem power output in the same ratio. Where an incoming filter is used, the modem power will be limited by emission from the nearest radiating structure on the network, as for the node modem power in the downstream case. This may be the house next door, or could be an item of street furniture such as a lamppost. Fig 80 therefore shows the upstream data capacity for a house with an incoming filter, with the modem power output limited by emission from an adjacent house at a distance of 20m. This calculation shows the capacity under nighttime conditions, which is the worst case due to the increased ingress noise. Because this is the limiting condition for what can be achieved, the daytime and unfiltered graphs are omitted for the upstream case.

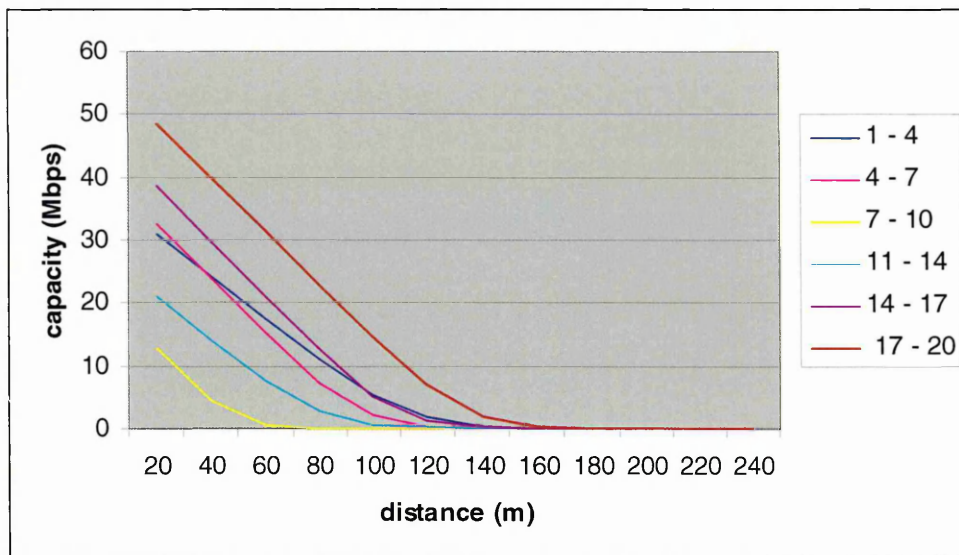


Figure 80: Night-time upstream capacity with incoming filter

On the basis of fig 80 it can be seen that the available upstream bandwidth is very low at distances beyond 120m. This means that in a system that is designed to meet MPT1570 emission limits it will be necessary to use upstream repeaters. For the repeatered upstream case each hop will have the characteristics shown in fig 80.

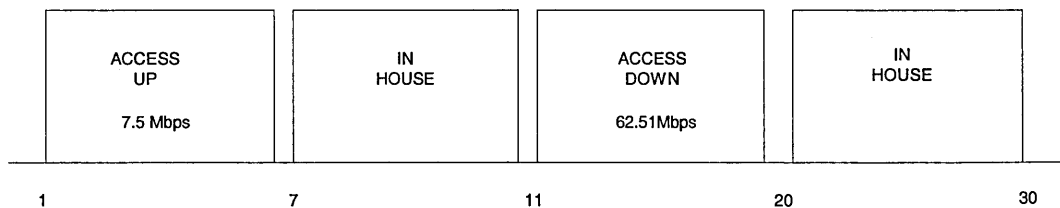
9.4. A Band Plan for PLT Systems

Based on the capacity predictions, it is possible to formulate a band plan to provide the maximum capacity with minimum radio interference. The capacities of the various frequency sub-bands are summarised in table 28, which is based on a hop distance of 100m and the use of incoming filters in houses that take the PLT service.

Table 28: Capacities of sub-bands

Band (MHz)	Upstream capacity (Mbps)		Downstream capacity (Mbps)	
	day	night	day	night
1 - 4	8.7	5.38	9.31	5.89
4 - 7	6.35	2.12	15.02	8.34
7 - 10	0.02	0.01	4.16	2.11
11 - 14	0.53	0.76	25.06	26.75
14 - 17	2.91	5.26	17.82	21.71
17 - 20	12.21	14.67	19.63	22.19

It is clearly necessary that the PLT service provides an acceptable performance throughout the diurnal cycle, so that a sub-band is only usable if it provides a useful data rate under the worst condition. Choosing the best sub-bands in each direction on that basis gives the optimum band plan shown in fig 81.

Figure 81: Proposed PLT band plan

In formulating the plan, the best of the sub-bands in terms of diurnal capacity have been chosen for use by Access systems. The bands that are unsuitable for Access system use have been designated as in-house allocations, on the basis that the short hop distances required for in-house systems should be capable of being covered with powers low enough to avoid undue radio interference,

despite the greater ingress noise in these bands. No attenuation data for in-house wiring was available to this study to validate that assumption and therefore no predictions of capacity have been made for in-house systems.

The data rates quoted for the Access sub-bands are the aggregate of night capacities for the upstream band and the day capacities for the downstream band, which represent the highest sustainable data rates through the diurnal cycle for the chosen 3MHz measurement sub-bands.

Fig 81 showed how the HF spectrum would be partitioned into sub-bands for PLT use. It is now necessary to examine how each sub-band would be used in a practical network. First, the case of a maximum capacity network will be considered; this being defined as a network in which the limiting factor is the capacity of the LV PLT systems, rather than the backhaul network. A maximum capacity network will therefore typically use a fibre optic backhaul network, which has a capacity far greater than can be achieved with PLT.

9.4.1. Downstream Band Plan – Maximum Capacity Network

The detail of the downstream band plan is shown in fig 82.

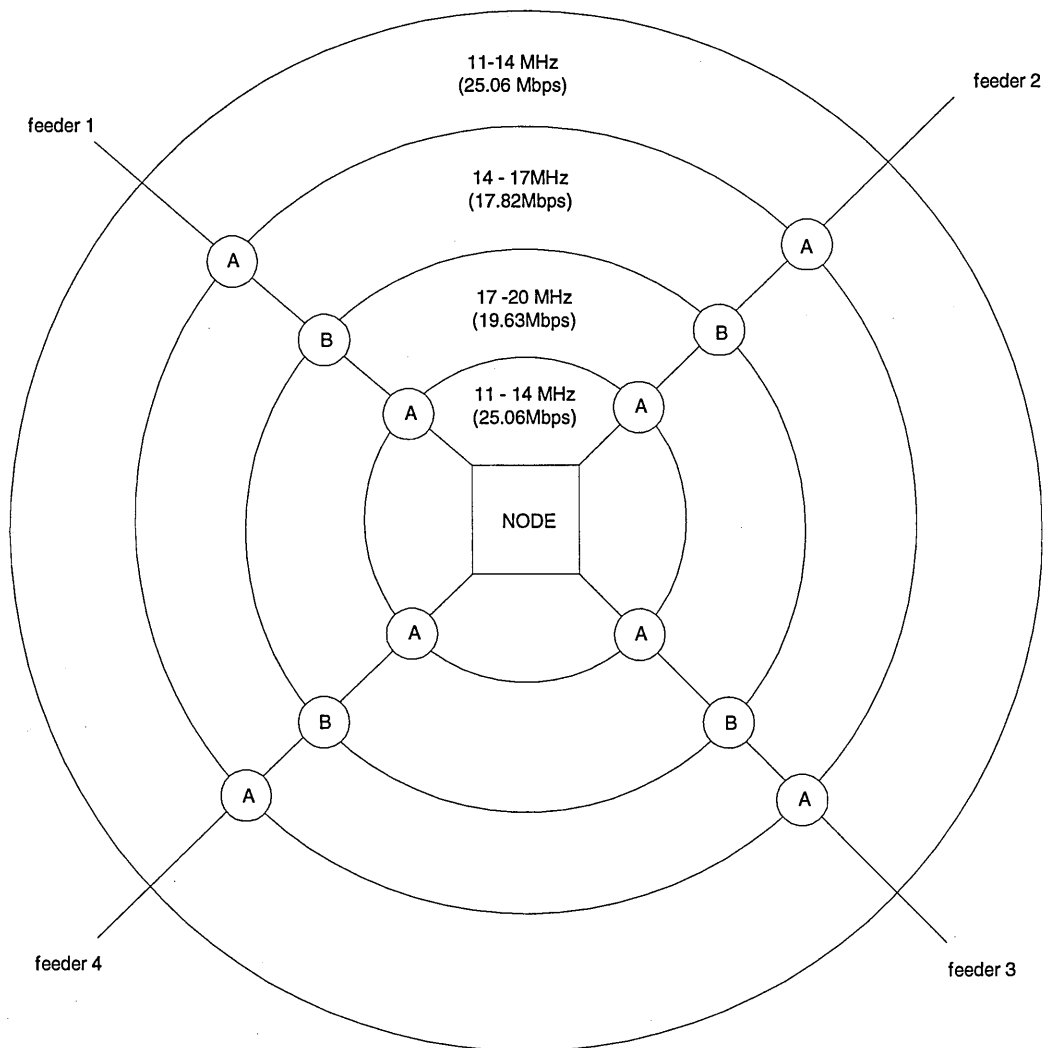


Figure 82: Maximum capacity network - downstream band plan

Fig 82 shows an idealised network, consisting of a centrally located node feeding four radial mains, along which the customers are located. In this configuration, the node would be located at a secondary substation, which represents the worst case condition. The gaps

between the concentric circles represent 100m, the specified maximum hop distance, giving a maximum feed distance of 400m, which was determined to be the longest feed at a 90% confidence level [Brannon 2005, pp33]. As all the feeders are coupled at the busbars, the sub-band with the greatest capacity is used at the node, and this sets the maximum data capacity of the node, in this case to 8.26Mbps. Sub-bands are used more than once in the network and the letters in circles on the feeders show the repeat distances; which can be determined by counting the number of concentric circles passed between the same letters and multiplying by 100m. The circles on the feeders effectively show the location of the repeaters at which the frequency translations between sub-bands are made. The band plan for each individual feeder is shown in fig 83. The plan refers only to the repeater operating frequencies; subscriber modems will require the facility to select their operating band on the basis of the strongest signal received downstream from the node.

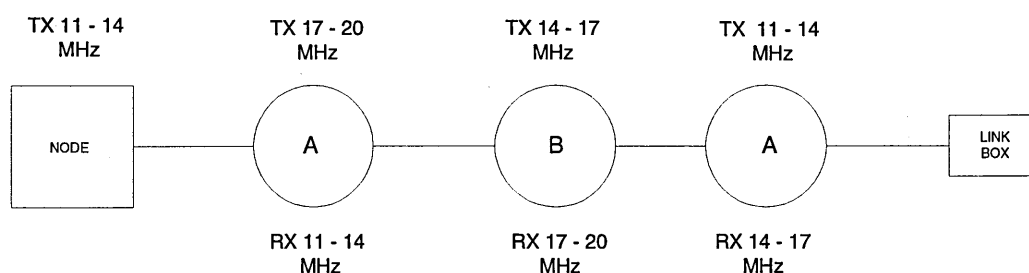


Figure 83: Frequency re-use plan for a feeder

The plan provides the separation of re-use of the same sub-band by the distances shown in table 29, which also

shows the attenuation between instances of the same frequency sub-band.

Table 29:: Repeat distances and electrical separation of downstream sub-bands

Sub-band (MHz)	Separation distance (m)	Electrical separation (dB)
11 - 14	200	70.7
14 - 17	400	174.4
17 - 20	200	85.3

Given the limitation on modem injection power resulting from the combination of building k factors and MPT1570 limits, the unwanted signals resulting from the frequency repeats will be typically at least 40dB below the ingress noise, thus having no effect on the operation of the system.

9.4.2. Upstream Band Plan – Maximum Capacity Network

The 6MHz of spectrum allocated for upstream operation is capable of supporting 7.5Mbps under worst-case, night conditions. The 4MHz to 7MHz sub-band can only support 2.12 Mbps at night, so that a simple frequency split using alternate sub-bands on alternate repeaters would limit the upstream data rate to 2.12Mbps. Also, by alternating frequency bands between hops, only 100m of separation would be achieved between the receiver and the unwanted transmitter, so that a receiver could receive a

wanted and an unwanted signal at similar levels. For this reason, the preferred mode of operation is to use the full 6MHz upstream band on each hop, with store and forward repeaters.

Operating the repeaters in store and forward mode will reduce the data capacity of the upstream route because of the need for a repeater to receive and store the complete message before re-sending it. This is shown in fig 84, in which the Y axis refers to the various stages of transmission up the feeder, R1, R2 - R3 are the repeaters between the node and the subscriber. The X axis shows the timing, in terms of the message length (m).

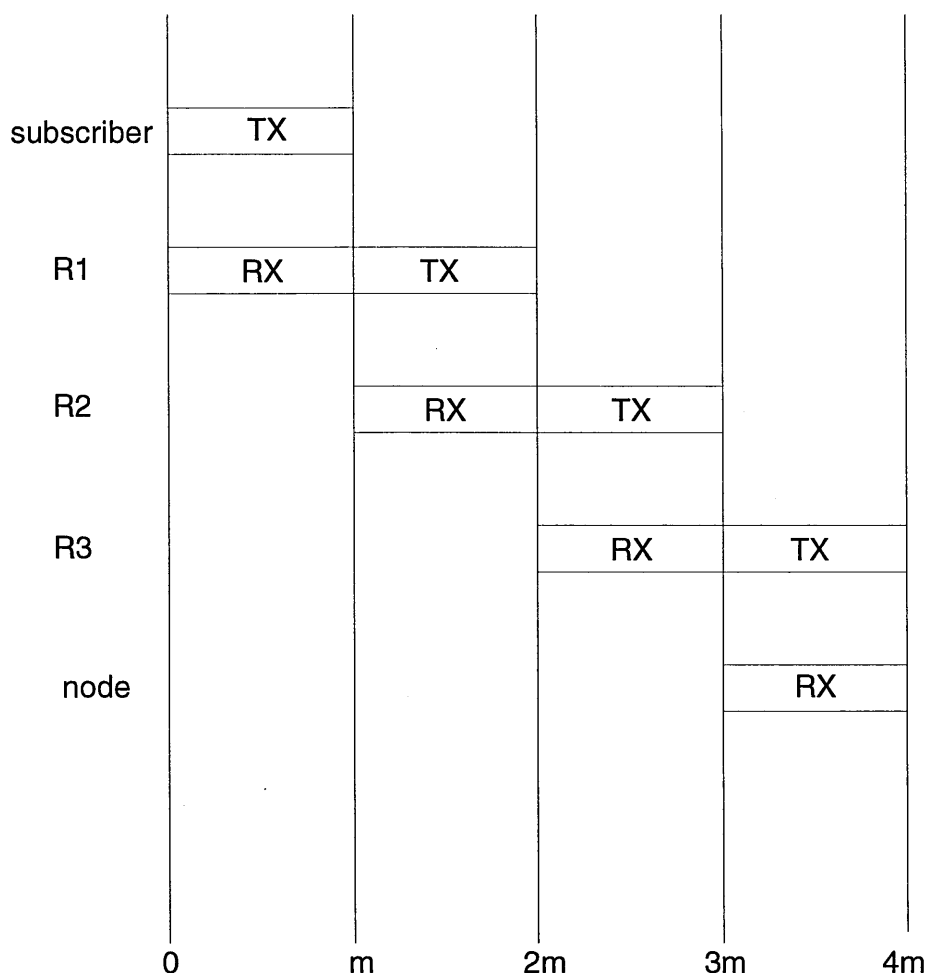


Figure 84: timing of store and forward repeaters

Equation 35 is derived from fig 84 by inspection.

Equation 35: system capacity with repeaters

$$C_{route} = \frac{C_{hop}}{1+R}$$

where C_{route} is the capacity of the PLT connection, C_{hop} is the capacity of a 100m hop in the frequency band used in Mbps and R is the number of repeaters in the route. As the hop capacity of the 1 MHz to 7MHz band is 7.5Mbps and a 400m route with 100m hops requires three repeaters, the upstream capacity is 1.875Mbps. Because the same frequency is used at each repeater for upstream operation there are no issues regarding frequency repetition, so an upstream band plan is not shown.

9.4.3. The Effect of Backhaul Network Capacity Limitations on a PLT System

As discussed in section 2.2.1.4 it may be necessary to use a public data transmission system for the backhaul network, and this may impose an economic or practical restriction of 2Mbps on the backhaul network capacity. This may be acceptable because each customer will be able to have data bursts of 2Mbps, which is comparable with current cable and ADSL offerings, and if contention ratios become unacceptable it is possible to add further remote nodes to the power network.

Reducing the data capacity of the PLT system to match the backhaul capacity means that a lower signal to noise ratio can be accepted and therefore the modem power injection can be reduced, resulting in lower emissions from the PLT system. The required signal to noise ratio can be calculated by rearranging the Shannon equation [equation 13] as equation 36.

Equation 36: Calculation of required signal to noise ratio for a given data capacity

$$SNR = 10 \times \log_{10} \left(2^{\frac{C}{W}} - 1 \right)$$

where C is the capacity in bits/sec and W is the bandwidth in Hz, and the SNR is in dB.

Given a required capacity of 2Mbps in a sub-band 3MHz wide, this suggests that SNR required is -2.3dB. However, consideration of the bandwidth efficiency of an ideal system reveals that there is a minimum signal to noise ratio limit of -1.6dB for error-free operation, which is often referred to as the 'Shannon limit' [Haykin, 1988, pp48-50]. This is a theoretical limit and operation at negative signal to noise ratios is not practical, but by using a turbo coded QPSK it should be possible to achieve error-free operation at approximately 0.5dB signal to noise ratio [Oberg 2001, fig 6.52, pp328].

The emissions at 2Mbps capacity were therefore calculated using equation 37, which is derived from the upstream power budget for a hop [equation 4] and the 0.5dB signal to noise ratio for turbo coded QPSK quoted by Oberg. Equation 37 thus allows the worst-case emission to be calculated from a knowledge of the signal to noise ratio at the receiver, rather than facilitating calculation of the signal to noise ratio at the receiver with a fixed emission limit as is the purpose of equation 4.

Equation 37: Upstream emissions for a backhaul limited PLT system

$$E_{upstream} = 0.5 + hopatt + ingress + k - 10m_att$$

where 'hoppatt' is the cable attenuation for a 100m hop, 'ingress' is the ingress noise at the substation busbars, 'k' is the k factor of the house and '10m_att' is the attenuation of 10m of the cable. This formula assumes that the sending house is fitted with an incoming filter and that the maximum emission comes from an adjacent, non-service taking house at 10m distance, with no filter.

The corresponding downstream calculation is shown in equation 38, which is derived from the downstream power budget equation [equation 3] and the 0.5dB signal to noise ratio for turbo coded QPSK quoted by Oberg.

Equation 38: Downstream emissions for a backhaul limited PLT system

$$E_{downstream} = 0.5 + hopatt + ingress + k - 20m_att$$

where '20m_att' is the attenuation of 20m of the main; the maximum emission coming from the house nearest the substation.

The assumptions and parameters used in this assessment are the same as used for the capacity calculations.

Based on the above method, the emissions from an underground system running at 2Mbps in the 3MHz sub-bands are shown in figs 85 to 89. All of these graphs are based upon a 100m PLT hop, as for the maximum capacity network calculations. For the upstream case with filters, the worst-case emission is assumed to arise from a house with no filter, 10m run of main from the subscriber.

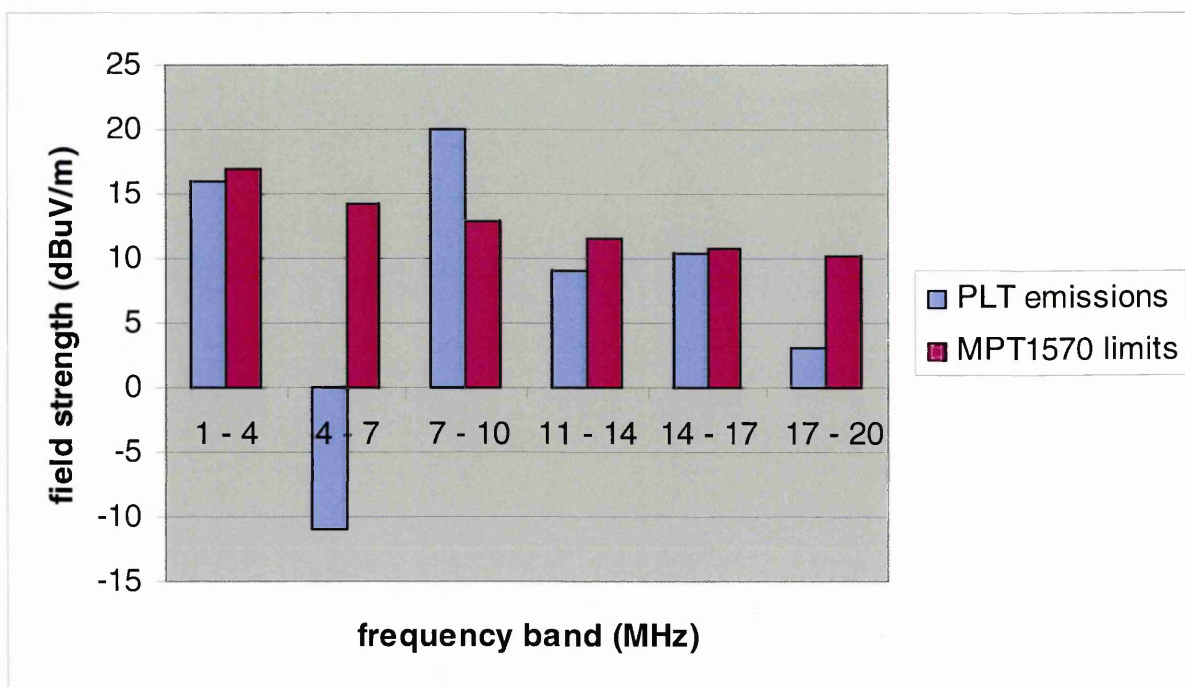


Figure 85: Daytime downstream emissions for backhaul limited system (2Mbps) with incoming filters

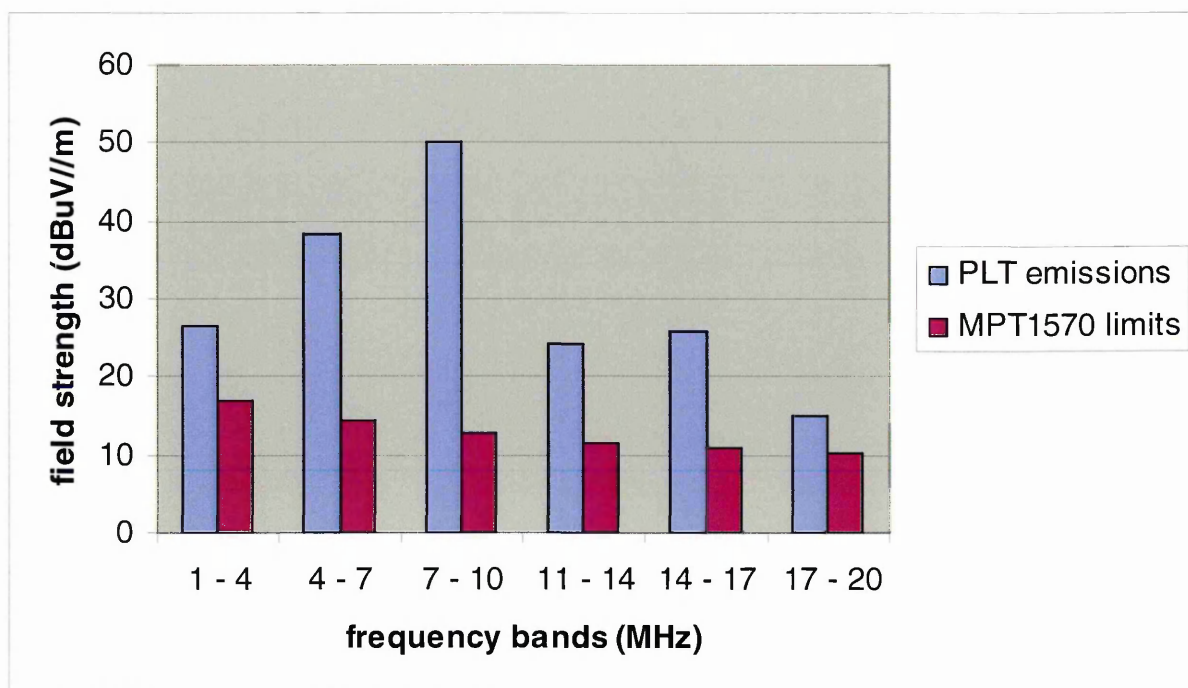


Figure 86: Daytime downstream emissions for 2Mbps backhaul limited system with no filters

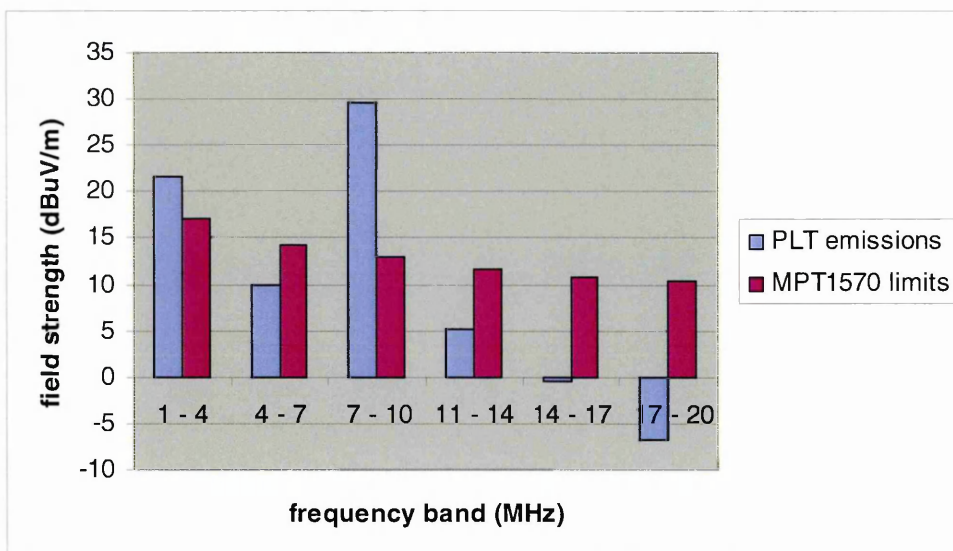


Figure 87: Nighttime downstream Emissions for Backhaul Limited System (2Mbps) with incoming filters

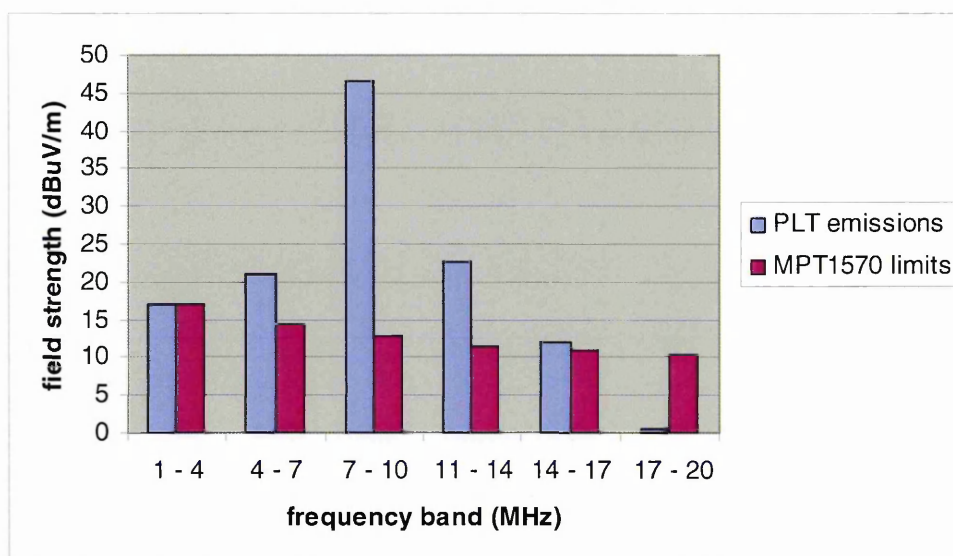


Figure 88: Nighttime upstream emissions for backhaul limited system with incoming filters

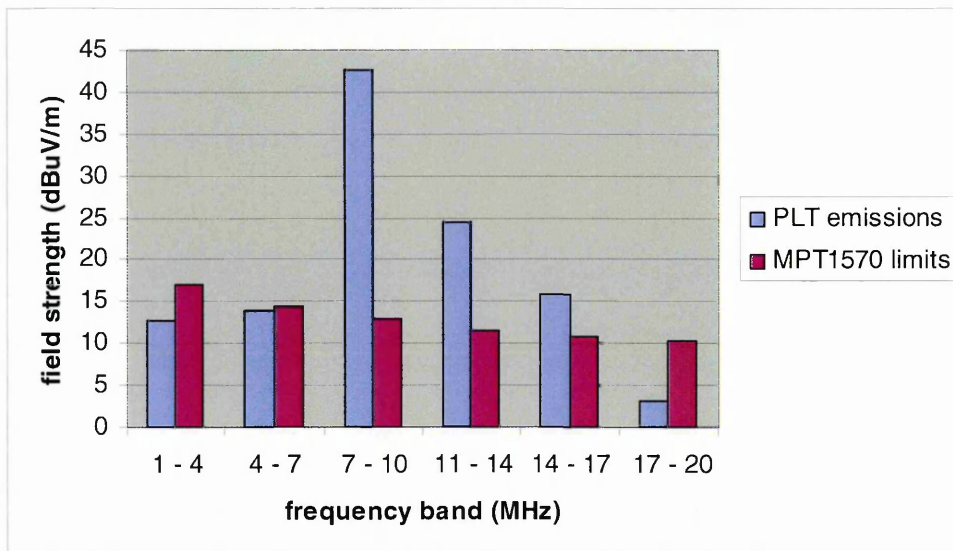


Figure 89: Daytime upstream emissions for backhaul limited system with incoming filters

In figs 85 to 89, each 3MHz sub-band shown has a capacity of 2Mbps. Fig 85 shows that for daytime operation, only the 7MHz to 10MHz band is not compliant with MPT1570 if incoming filters are used. Fig 86 shows that even for daytime operation MPT1570 compliance cannot be achieved without using incoming filters, even when using the minimum injection power for 2Mbps operation. For downstream operation the function of the incoming filters used at the subscriber premises is to reduce ingress noise at the modem receiver. Fig 87 confirms that, even with incoming filters and a limited data rate, the 1MHz to 4MHz and 7MHz to 10MHz bands are unsuitable for downstream PLT operation within the MPT1570 limits with 100m hops. Finally, fig 89 confirms that only 1MHz to 7MHz is suitable for upstream operation. Therefore the 7MHz to 10MHz band is not used for access systems within

the proposed band plan because of its unacceptable ingress noise levels.

In addition to verifying the band plan, the consideration of the backhaul limited system reinforces the role of ATPC in minimizing PLT interference, as discussed in section 6.6.4 of this thesis.

9.5. Intermodulation Considerations

A further important consideration is the effect of the proposed band plan on the intermodulation products. An unsuitable band plan could result in IMPs from the transmitter section of a frequency translating repeater falling within the receive band and blocking the incoming signal. The situation would be particularly complicated with OFDM equipment, where the IMP spectrum in a 1024 carrier system could contain so many products that it would appear as white noise, leading to a general decrease in signal to noise ratio that would affect the performance of the system while being difficult to diagnose. The situation is even more complicated with DS-SS modulation.

Because of the inherent difficulties it is not possible to make a numerical assessment to find where the IMPs of the proposed band plan would lie. However, fig 72

provides some guidance on the advantages of the proposal. As power reductions of the order of 15dB are possible by, for example, the use of the 17MHz to 20MHz band instead of the 4MHz to 7MHz band, then using the 'best' bands will produce significant decreases in IMPs. It should be noted that, as IMPs are formed by a multiplicative process the reduction in their level is greater than the power reduction; eg reducing the power input by 1dB will result in IMPs 3dB lower in the case of a third-order product. On this basis, the proposed band plan should result in a significant reduction of IMPs as compared with those caused under existing conditions, resulting in improved efficacy of frequency band 'notching' whatever modulation technology is in use. It should also result in a reduction of broadband noise in multi-carrier systems such as OFDM, where the IMPs resulting from the interaction of large numbers of carriers would appear as an increase in the noise level, which might compromise the PLT transmissions by appearing in the modem receiver band.

9.6. Summary of band planning considerations

From the information presented in this chapter, it is possible to draw the following conclusions:

- a major determinant of PLT system performance is the ingress noise
- band planning for PLT must take into consideration the diurnal variation in ingress noise
- because of excess ingress noise, some parts of the HF spectrum cannot be used efficiently for access PLT systems
- the currently proposed ETSI band plan is wasteful in terms of spectrum use by denying access systems the use of some of the quietest frequency bands
- for the proper operation of access systems within the emission limits proposed in MPT1570, it is necessary to use incoming filters at the subscriber modems
- where the data capacity of the backhaul network is limited, the data rate of the PLT LAN segment should be restricted to the backhaul data rate to reduce radio interference
- to provide the best spectral efficiency and to minimize operating problems between adjacent PLT nodes the band plan should divide the frequency spectrum into upstream and downstream bands
- advantage can be taken of the attenuation of the distribution system cabling to enable the repeating of frequencies within the same distribution network, provided that a correct frequency plan is used.

- The modem injection power reduction facilitated by the proposed band plan should improve the overall system noise floor by reducing the level of any IMPs created by the operation of the PLT system.

Of course, the advantages of the band plan in terms of limitation of radio interference will only be obtained if the PLT modem power injection is limited to the minimum necessary to sustain the link. PLT modems should therefore be fitted with some type of Automatic Transmitter Power Control aimed at interference minimization. Also, due attention should be paid to the commissioning of systems to ensure that the minimum necessary power is used.

9.7. Effect of the Band Plan on the Conducted Limits

In considering a band plan, the effect of the proposal on the conducted limits must also be considered, as well as the emissions. Information on the level of the conducted signals associated with the proposal can be inferred from section 8.1.3. It was shown that the current conducted limits of CISPR 22 were not sufficiently low to ensure the protection of radio services, and that a reduction of at least 27dB in the CISPR 22 limits was needed (mains port class B) to meet MPT1570 on the networks tested in Scotland. Because the current CISPR 22 limits result in emissions in excess of the MPT1570 limits and the

proposed band plan is based upon conformance to MPT1570, it is evident that the CISPR 22 limits are more likely to be met by equipment conforming to the proposed band plan.

9.8. Modulation and Coding Requirements

While the foregoing sections set out a band plan to provide optimum data rates while minimizing radio interference, achieving the performance predicted by Shannon's equations requires careful attention to the modulation and coding systems. The requirements are considered in this section.

In choosing modulation and coding systems for PLT a number of factors have to be taken into account:

- meeting the Shannon limits
- dealing with multi-path transmission caused by reflections within the distribution and house wiring systems
- dealing with the transient interference described in section 8.2.8 of this thesis.

9.8.1. Achieving the Shannon Limits

Providing a transmission system that can achieve the Shannon limits requires an efficient line code. The perfect code has not yet been invented. As an example [Mackenzie 2005], the 1992 Galileo space mission needed 60% more transmitter power to achieve error-free

transmission than it would have with a perfect code.

"NASA spent \$80 million to upgrade the deep space network which is used to receive signals from spacecraft and the signal to noise ratio increased by 25%. A code that could let you communicate at the Shannon limit would get you twice that improvement for free" [ibid]. It is now possible to get within 10% of the Shannon limit, using a turbo code called Low Density Parity Check (LDPC).

9.8.2. Dealing with Transient Interference

In section 8.3 a band plan was proposed that offered a maximum data rate of 19.63Mbps within the radio interference limits. At that data rate the bit duration is 0.051 μ s. From table 25 it can be seen that a 10 μ s transient can be expected every 20minutes if they are evenly distributed throughout the day, while fig 70 shows that the occurrence of transients at a level capable of affecting PLT transmissions is more frequent. At the 19.63Mbps data rate a 10 μ s transient will affect 196 bits. It is not practical to correct such an error using an error correcting code even with bit interleaving, because the required redundancy would reduce the data rate too much. While ARQ techniques that repeat errored blocks could be used to cope with the comparatively infrequent transient hits (such a mechanism is incorporated into TCP/IP) it must be remembered that a PLT route consists of multiple hops on which transient

events are unlikely to be correlated, thus increasing the amount of message repeats and reducing the user throughput of the system.

An alternative is to use OFDM to reduce the symbol rate on the line. In the case of the 19.63Mbps transmission, using 1024 carrier OFDM with two-state modulation of the carriers would increase the symbol duration per bit to 52 μ s, thus rendering the system susceptible only to the longer transients, which table 25 suggests are far less frequent. OFDM can therefore offer enhanced performance with less complexity than other solutions [section 5.6.2].

9.8.3. Dealing with Multipath Interference

The complexity of the distribution system cabling means that multipath interference is likely to occur; that is probably the cause of the more extreme variations in attenuation and phase shift seen in the graphs in section 8.2.5.1. The efficiency of a modulation system in dealing with multipath is related to the symbol duration. By introducing a guard period between each symbol the efficacy of OFDM against multi-path can be improved further, because, "...The reflected signals should have time to fade away before the detection of the next symbol is started" [Oberg 2001 pp260]. The guard period between

symbols should therefore be incorporated into the operation of OFDM systems used for PLT.

9.9. Summary

This chapter has presented a method of deriving a band plan for PLT, capable of providing useful data capacities within the MPT1570 proposed emission limits. It has been shown that the ETSI access/in-house co-existence band plan is inefficient because some parts of the spectrum with the best diurnal signal to noise ratios as an access system are designated for use indoors. A band plan is proposed that can provide useful data capacity for the PLT system while meeting the MPT1570 emission limits and the CISPR 22 conducted limits. The operation of the band plan in an LV distribution system has been discussed. The modulation requirements to deal with the measured levels of transient interference have been examined.

The next, and final, chapter presents the conclusions of the study and critically reviews the outcome of the research programme. Areas requiring further research are identified.

10. CONCLUSIONS

This thesis has described a unique study of the optimization of band planning for PLT systems, based on a comprehensive data set acquired from an extensive measurement programme. The conclusions arising from the research programme are as follows:

1. The trial systems tested do not meet either the conducted or radiated emission limits currently proposed
2. A band plan has been proposed that permits operation of PLT Access equipment with a reduced potential for radio interference, within the proposed emission limits.
3. Meeting the MPT1570 emission limits will result in conformance with the CISPR 22 conducted disturbance limits
4. OFDM is the preferred modulation system to ensure adequate performance of the PLT system in the presence of transient noise.
5. Automatic Transmitter Power Control should be used in the modems to minimize the radio interference potential of PLT systems.
6. Error correction must be applied to each PLT hop; reliance on TCP/IP for end to end error correction is not adequate for optimum system performance.

7. The use of an incoming filter at a subscriber's premises is essential in controlling radio interference while maintaining PLT system performance.

10.1. Critical Review

This research programme has been successful in that the combination of the measurement programme and the theoretical evaluation has identified the major areas affecting the performance of broadband PLT systems. A means of optimising system performance by correct band planning has been proposed. Limitations of the study are as follows:

- attenuation measurements were made on only two networks; thus the results may not be universally applicable
- because no equipment exists that conforms to the proposed band plan, it was not possible to perform experiments to validate the data capacity predictions by operating PLT equipment within the proposed band plan and collecting error rate data over a diurnal operating cycle, which is the minimum testing required for validation.
- While this thesis provides useful information on the band planning process it does not address the problem of achieving a relationship between radiated and conducted emissions that is the holy grail of

the standardisation bodies because it would allow a product standard to protect radio services

- The study is restricted to the use of the HF band for broadband PLT and does not consider the possibility of operating in the VHF and higher bands to avoid ingress noise problems
- Intermodulation product (IMP) measurements were only carried out in the laboratory, not on LV distribution networks.

10.2. Proposals for Further Work

The limitations of the study, as described in the critical review, lead to a number of suggestions for further work, as follows:

- Further analysis of the available data in order to derive a statistical relationship between conducted and radiated signals, leading to the development of an empirical model based on the probability of a given level of PLT signal injection resulting in a defined probability of radio interference for a percentage of time at a percentage of locations.
- Measurement of attenuation on other LV distribution networks having different design

parameters, numbers of connected premises and cable types

- Measurement of conducted intermodulation products on LV distribution networks
- Measurement of radiated intermodulation products from LV distribution networks, subject to the significant levels of conducted IMPs being found.
- Bit Error Rate testing of systems working within the proposed band plan and emission limits to confirm the capacity predictions
- An investigation of the use of frequencies above 30MHz for PLT.
- More testing of in-house PLT systems

APPENDIX A: FIELD STRENGTH LIMITS

Throughout this thesis, reference is made to a number of field strength limits, which are used on graphs showing the PLT measurements and in the capacity calculations. This appendix explains the derivation of these limits. The limits are divided into the following categories:

- Regulatory limits, proposed for the protection of radio services
- Service planning limits, used to define the typical field strengths expected for acceptable reception of radio services
- Predicted noise levels, derived from measurements and providing an estimate of the noise level to be found in a number of environments

A1 Proposed Regulatory Limits

This section provides information on the proposed regulatory limits referred to in this thesis. All of these limits are specified on the basis of measurement in a 9kHz measurement bandwidth using a peak detector. The limits are specified in terms of an electric field strength measured in dB relative to 1 μ V/m (dB μ V/m) using a magnetic loop antenna. Such antennas measure current, rather than voltage, but the limits are converted to voltage by adding a factor of 51.5dB [MPT1570 2000, note,

para 8.5, PP14] to allow them to be expressed as electric field strengths.

A.1.1 MPT1570

The MPT1570 limit used in this thesis is taken from part C of MPT 1570 [MPT1570 2000, part C, pp14-15], which specifies a limit as shown in equation 39 for the frequency. Range of interest.

Equation 39 MPT 1570 electric field limit

$$E_l = 20 - 7.7 \times \log_{10} f [MHz]$$

where f is the spot frequency at which the limit is measured and E_l is the electric field strength limit, in dB μ V/m.

A.1.2 Other Regulatory Limits

Due to difficulties in obtaining the original source documents in English, the other European limits were taken from the BBC R&D document on emission limits, which also provides details of the BBC 0.5dB noise floor increase proposal [Stott 2001]. These limits are defined by equations 40 to 43, in each of which f is the spot frequency at which the limit is measured and E_l is the electric field strength limit, in dB μ V/m.

Equation 40 NB 30 German limit (3m)

$$E_l = 40 - 20 \times \log_{10} f [MHz]$$

Equation 41 NEDAP Netherlands 1.5MHz - 29MHz limit (3m)

$$E_l = 40 - 7.7 \times \log_{10} f [MHz]$$

Equation 42 BBC proposal (20m)

$$E_l = 21.8 - 8.15 \times \log_{10} f [MHz]$$

A2 Noise Levels

The noise levels are taken from ITU-R372-6 [ITU 1994]. This section describes the derivation of the man-made noise level lines from that document. It is necessary to determine the field strength in the correct measuring bandwidth for a dipole in free space, in terms of the noise coefficients specified in the document for the type of environment required. The noise field strength E_n , in bandwidth B (Hz), in terms of the external noise factor F_a , at frequency f (MHz) is given by equation 8 of P.372-6, shown here as equation 43.

Equation 43 Noise field strength in bandwidth B

$$E_n = F_a + 20 \times \log_{10} f [MHz] + B - 99.0 \text{ } [dB\mu V / m]$$

For a measurement bandwidth of 9kHz, this becomes equation 44.

Equation 44 Noise field strength in 9kHz bandwidth

$$E_n = F_a + 20 \times \log_{10} f [MHz] + 39.54 - 99.0 \text{ } dB\mu V / m$$

The median value for F_a in a residential area is given by using table 1 and equation 11 of ITU-R P.372-6, which gives equation 45.

Equation 45 Median value of F_a for a residential area

$$F_{am} = 72.5 - 27.7 \times \log_{10} f [MHz]$$

Substituting equation 45 into equation 44 gives the equation used for the ITU-R residential noise floor line in the graphs in this thesis; equation 46.

Equation 46 ITU-R Residential noise electric field strength

$$E_{residential} = 13.04 - 7.7 \times \log_{10} f [MHz]$$

Using the same process gives equation 47 for the rural noise floor limit.

Equation 47 ITU-R rural noise electric field strength

$$E_{rural} = 7.7 - 7.7 \times \log_{10} f [MHz]$$

A3 Amateur Radio Field Strengths

This section shows the derivation of the expected field strength predictions for amateur radio.

The amateur S9 signal is based upon the pd required at the receiver antenna port to produce a S9 indication as being 50µV (34dBµV). The antenna factor for a resonant half-wave dipole¹⁷ is calculated using the formula relating the gain of an antenna to its antenna factor as shown in equation 48 [Williams 2001 pp236].

Equation 48: relationship of gain and antenna factor for a resonant dipole

$$G = 20 \times \log_{10} f - 29.79 - AF$$

where f is the frequency in MHz, G is the gain relative to isotropic in dB and AF is the antenna factor in dB.

As the gain of a resonant dipole relative to isotropic is 2.14dB, the equation can be rearranged as equation 49.

Equation 49: Rearrangement of equation 48 for calculation of antenna factor

$$AF = 20 \times \log F - 31.93$$

Using equation 49, the antenna factor for a dipole varies across the HF band as shown in fig 90.

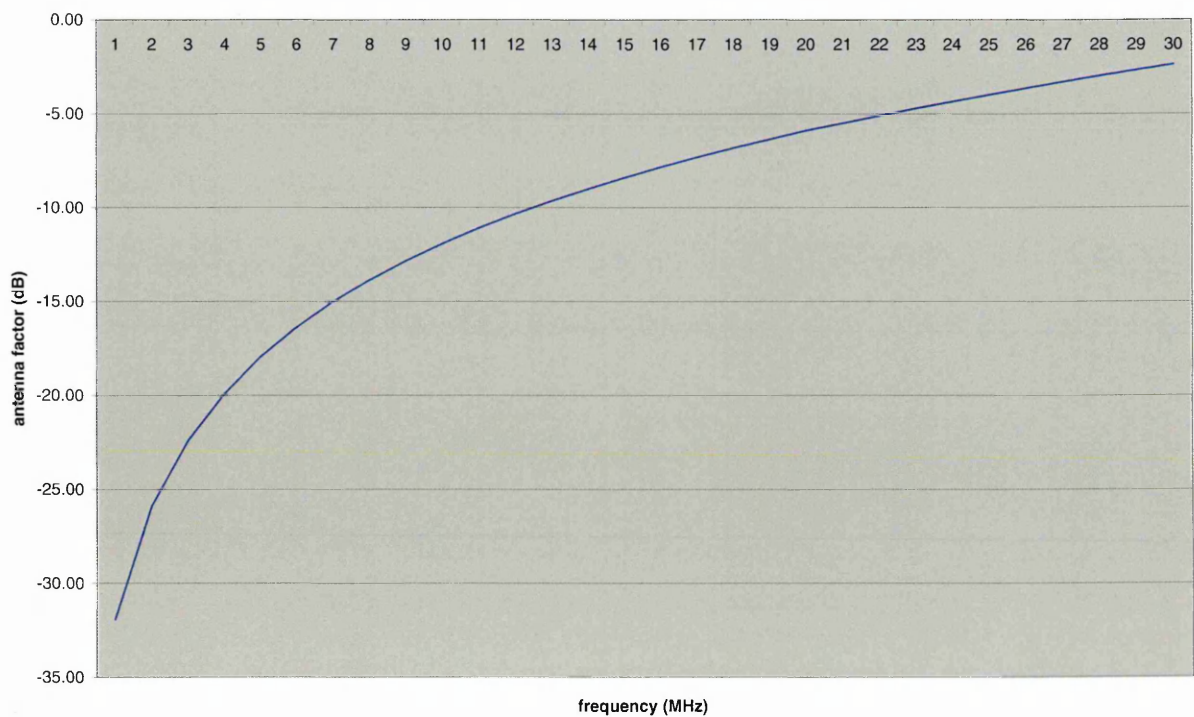


Figure 90: Variation of dipole antenna factor over the HF band

This is intuitively correct because the length of a resonant dipole increases with reducing frequency, thus

¹⁷ assumed to be a typical amateur antenna

leading to a greater output voltage with the same field strength. The theory was validated by Fraser Robertson at the Open University Open Area Test Site at Walton Hall by measuring the output voltage from a dipole and the field strength using the calibrated magnetic loop antenna for a signal at 8.44MHz. This produced a discrepancy of 0.47dB, so the calculated values are regarded as accurate enough for the purposes of this document.

The antenna factors within each amateur band were used to calculate the field strength for a S9 signal at each measurement frequency within the amateur bands. These calculations are used in the plots. Table 31 shows the frequency bands and the order of magnitude of the field strength required for a S9 signal. The relationship of the pd at the receiver antenna port to the field strength is as equation 50:

Equation 50: Calculation of signal voltage from field strength

$$e = E - AF$$

where e is the pd delivered to the receiver input in dBµV, E the field strength in dBµV/m and AF the antenna factor in dB. Rearranging and substituting the value of e (34dBµV) for an S9 indication, this becomes equation 51.

Equation 51: Field strength required for a S9 amateur signal

$$E = 34 + AF$$

which was used with equation 49 to derive table 30.

Table 30: Approximate field strengths for a S9 signal on the amateur bands

Frequency band (MHz)	Approximate field strength for S9 (dB μ V/m)
1.8 - 2.0	7
3.5 - 3.8	13.5
7.0 - 7.1	19
10.1 - 10.15	22
14.0 - 14.35	25
18.068 - 18.168	27
21.0 - 21.45	29
24.89 - 24.99	30
28.0 - 29.7	31

APPENDIX B: IMP MEASUREMENT VALIDATION

This appendix describes the tests carried out to validate the procedure described in section 7.1.9. A brief set of conducted measurements to prove the test procedure was carried out in the IFEC laboratory at the Walton Hall campus of the Open University on Tuesday 23 March 2004. The apparatus was set up according to the diagram in section 7.1.9.1.1, using Farnell and Marconi signal generators, a Minicircuits hybrid combiner network, an OU Low Voltage coupler and a Hameg spectrum analyser. After the initial tests, the spectrum analyser was replaced by a Rhode and Schwartz measuring receiver to facilitate more accurate measurements. The input circuit of the measuring receiver was protected with a fixed 20dB attenuator connected between the tee piece and the receiver input port.

B.1 Initial Tests

The purpose of the initial tests was:

- To establish the internal linearity of the test rig; ie the level of spuri that were generated within the signal generators and the hybrid combiner
- To measure the losses within the test rig
- To see if it was possible to detect IMPs from the mains network

- To establish the noise floor of the test rig.

The results of the initial tests are shown in table 31.

Table 31: Results of initial IMP tests

generator harmonic outputs				
signal generator	set frequency (MHz)	fundamental level (dBm)	2nd harmonic level (dBm)	3rd harmonic level (dBm)
Marconi	1	0	-46	-56
Farnell	2.5	0	-52	<-60
loss through hybrid combiner				
condition	frequency (MHz)	loss (dB)		
combiner only	1	3		
	2.5	2		
mains connected	1	8		
	2.5	12		

It can be seen from table 31 that all signal generator harmonic outputs are at least 46dB below the carriers.

The maximum loss through the test rig with a 50Ω termination is 3dB, as would be expected when using a hybrid combiner, increasing to 12dB with the mains coupler connected, due to the miss-match caused by the impedance of the mains network.

Testing with the mains connected did not show any significant IMPs, so it was decided to construct a mixer circuit to act as a harmonic generator, to simulate the effect of a non-linearity in the mains network. The

harmonic generator consisted of two diodes connected in anti-parallel mode, with a series capacitor of 8nF, rated at 250Vac working voltage, to limit the current at the 50Hz mains frequency. This is shown in fig 91. The circuit was assembled in a 'safe-block' mains connector for the tests, but has now been assembled into a 13A plug-top to facilitate field use.

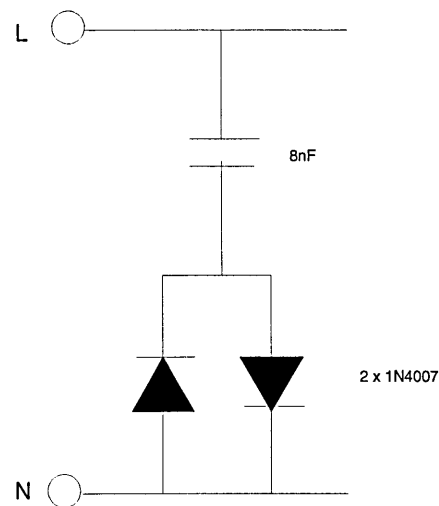


Figure 91: Harmonic generator

A series of tests were undertaken using the harmonic generator of fig 91 to mix the signals from the test rig. It was found that the harmonic generator provided a considerable enhancement of the IMPs, and the signals it produced could be identified easily because they were modulated at 100Hz. The modulation is believed to be caused by the variation in the working point on the diode V/I curve as the current through the diodes varies

throughout a cycle of the mains frequency¹⁸. This causes a cyclic variation of the diode voltage drop and hence a variation of the amplitude of the harmonic voltage. The modulation frequency is 100Hz, rather than 50Hz, because each diode deals with a half-cycle of the mains waveform. This effect has been noted when monitoring noise on the mains in the LF band, where television line timebase harmonics have been found to carry a 100Hz square wave modulation [Brannon 1995 pp60].

The tests were carried out using frequencies chosen in accordance with the calculations shown earlier to provide known intermodulation products. The results of the tests are shown in the following graphs. For each test, the following measurements were made:

- Levels of the carrier frequencies and the expected IMP frequencies
- A scan for products on frequencies not predicted by the simple analysis

Measurements were taken under the following conditions:

1. Harmonic generator connected
2. Harmonic generator disconnected
3. Mains disconnected

¹⁸ the mains frequency RMS current though the diodes is approximately 0.6mA

4. Mains disconnected and one signal generator switched off.

The purpose of these measurements was to establish:

- The level of IMPs caused by the harmonic generator
- The levels of IMPs occurring in the mains network
- The level of spuri generated within the test rig.

In the results that follow it should be noted that the noise floor of the test rig was -5dB μ V.

B.1.1 Test 1: 1MHz and 2.5MHz

The inputs for test 1 were as shown in table 32 and the measured levels are shown in fig 92.

Table 32: Inputs for IMP Test 1

	inputs	
	F1	F2
Frequency (MHz)	1	2.5
Level (dB μ V)	79	71.5

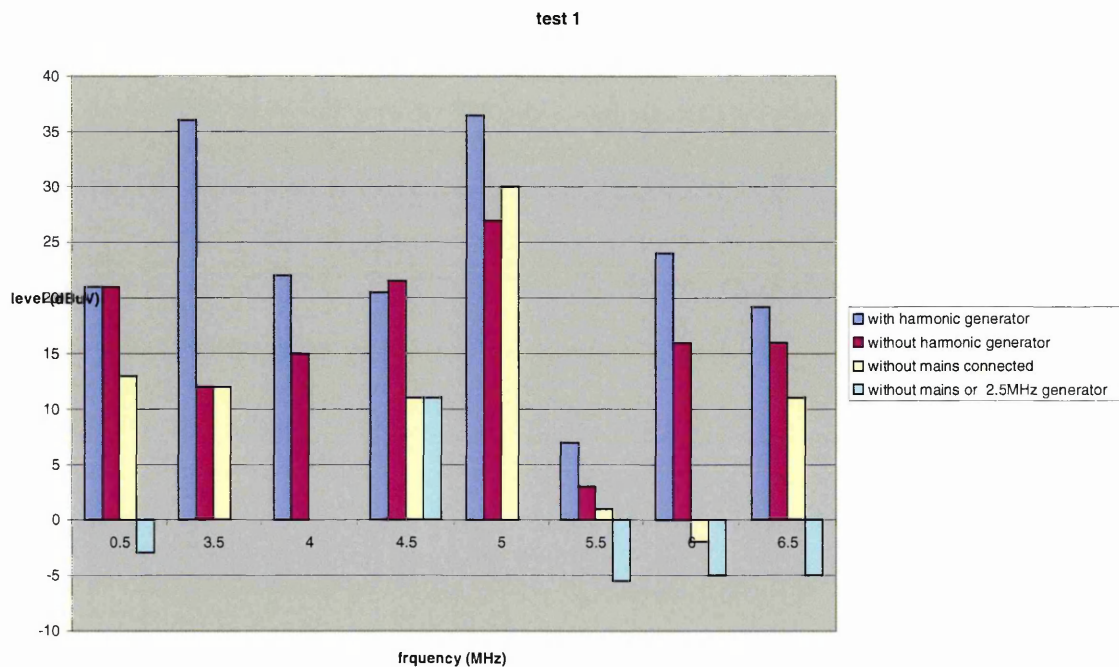


Figure 92: Measured intermodulation products; test 1

It can be seen that the harmonic generator provided a significant increase in level of the intermodulation products, of the order of 22dB at 3.5MHz. The product at 3.5MHz must have been produced within the test rig, because it did not change when the mains was disconnected. Because it disappeared when the mains was disconnected, the product at 6MHz clearly occurred within the mains and had a magnitude of 16dB. At 5MHz the intermodulation product was about 3dB higher when the mains was disconnected; it can only be assumed that this was a result of a low mains impedance at that frequency loading the test rig and reducing the level of an internally generated spurious signal.

B.1.2 Test 2: 2.5MHz and 3MHz

The inputs for test 2 were as shown in table 33 and the measured levels are shown in fig 93.

Table 33: Inputs for IMP Test 2

	inputs	
	F1	F2
Frequency (MHz)	3.0	2.5
Level (dBμV)	86.6	87.4

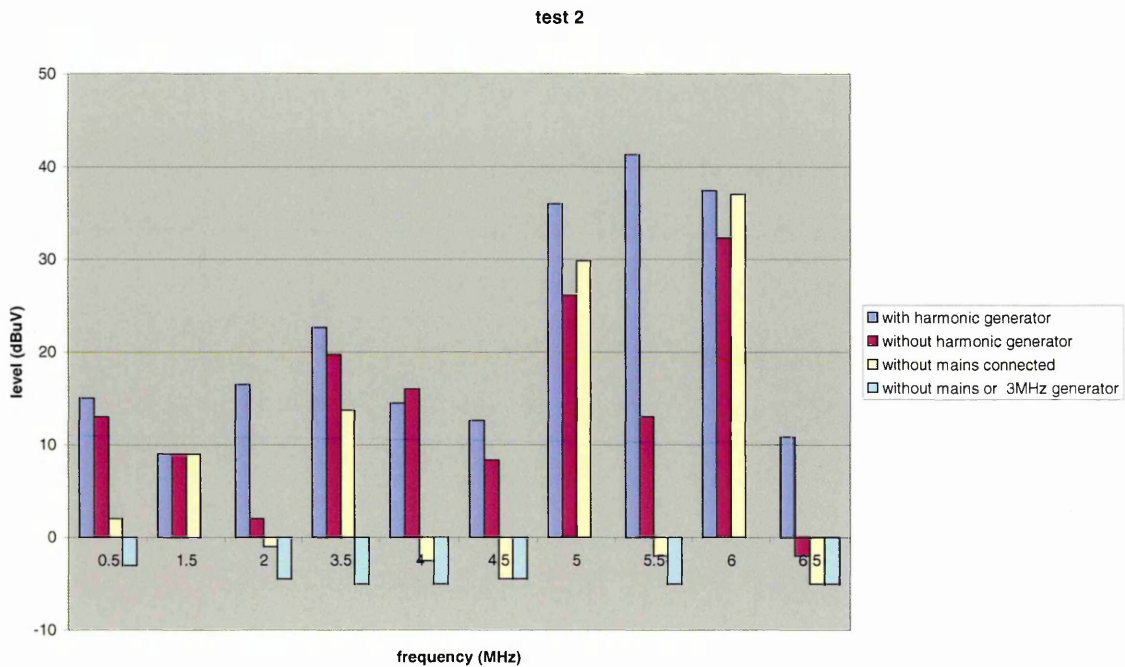


Figure 93: Measured Intermodulation Products - Test 2

Again, the results show a number of frequencies where the level of the IMPs is reduced when the mains is connected,

clearly indicting that they are generated within the test rig. But at 0.5MHz, 2MHz, 4.0MHz, 4.5MHz and 5.5MHz there is clear evidence of IMP generation within the mains wiring, with a fall of up to 15dB (at 5.5MHz) without the mains connected. Each of these frequencies is an even order IMP (2nd or 4th order), while odd order IMPs are much lower in level. The composition of the largest product (5.5MHz) was the simple sum of the two test frequencies (ie a second-order IMP).

B.1.3 Test 3 4MHz and 5.5MHz

The inputs for test 3 were as shown in table 34 and the measured levels are shown in fig 94. For this test, a wider frequency range was used for the measurement of potential IMPs, to cover the ETSI 'in-house' frequency band from 10MHz - 30MHz.

Table 34 Inputs for IMP Test 3

	inputs	
	F1	F2
Frequency (MHz)	4.0	5.5
Level (dBµV)	86.5	87.1

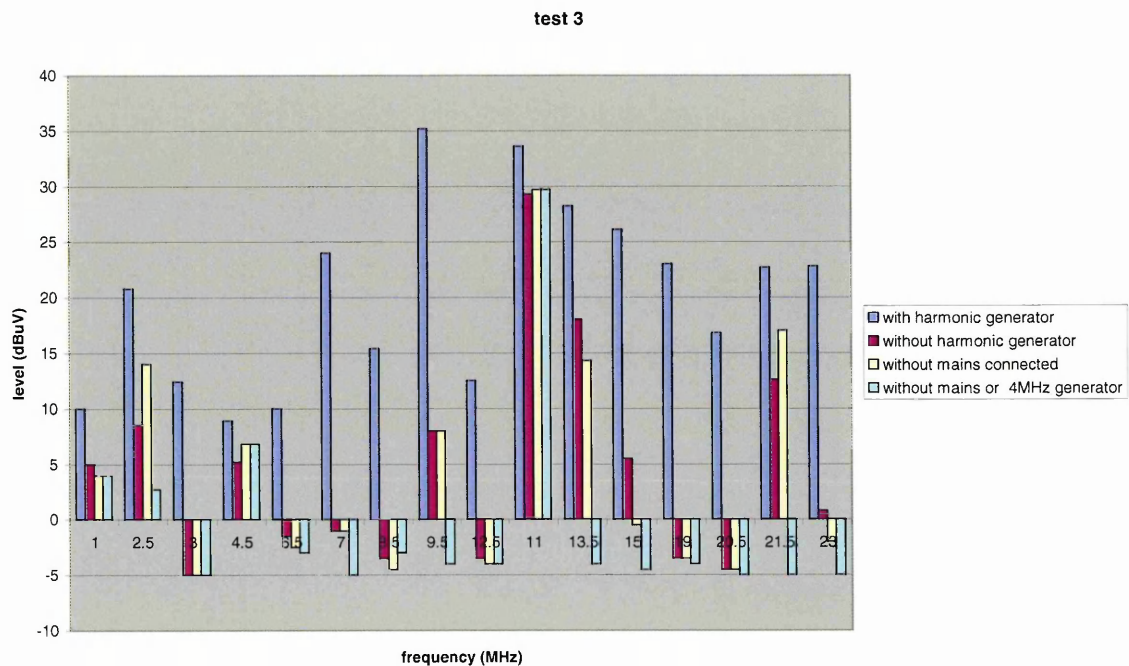


Figure 94: Measured intermodulation products - test 3

In this test, there is is are three mains generated IMPs:

- 13.5MHz/4dB
- 15MHz/6dB
- 23MHz/3dB

where the levels stated are the level of the mains IMP above the IMPs generated within the test rig and represented by the difference between the 'without harmonic generator' and the 'without mains connected' bars on the graph. Again there is evidence that the IMPs generated within the test rig are being suppressed to some extent because of loading by the impedance of the mains.

APPENDIX C: IMPEDANCE MEASUREMENTS

This appendix gives details of the results of the calculation of mains impedance from the attenuation measurement data files, following the method explained in section 7.1.2.

C.1 Measured Impedances

Each measurement is shown as a plot of S_{11} and S_{22} against frequency. The total frequency span varies between plots because in some cases there was too much ingress noise at certain frequencies for reliable measurements. The results obtained are shown in figs 95 to 101. In each case, there are two plots. S_{11} represents the impedance at the remote point (building or link box) while S_{22} is the impedance at the substation busbars, the two measurements having been made simultaneously while the transfer function between the two locations were being measured.

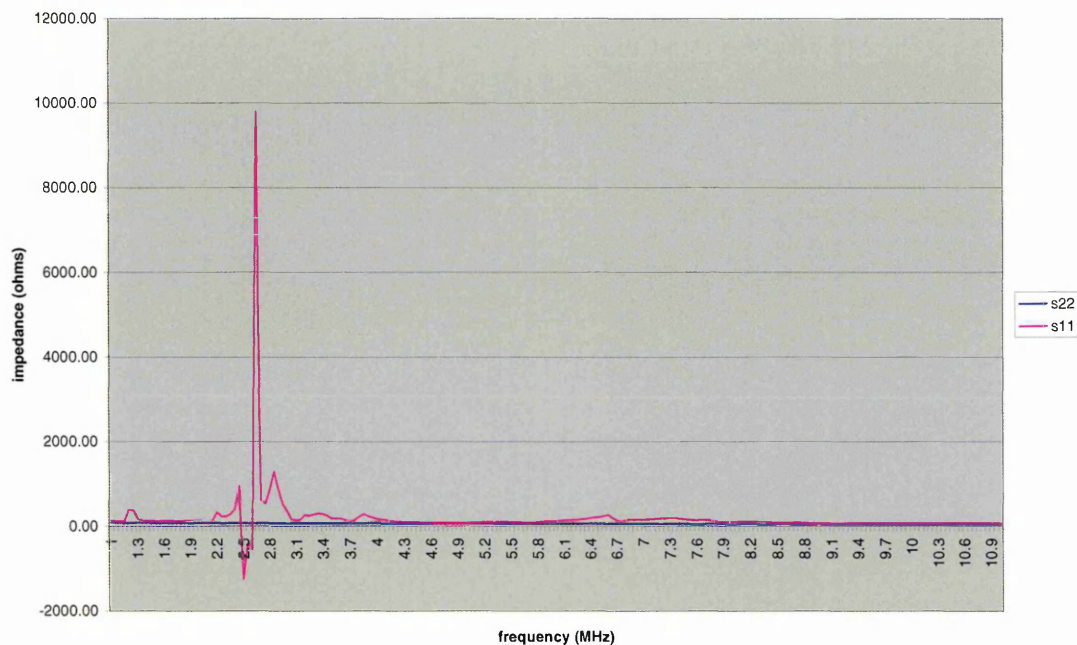


Figure 95: Impedance - house A to substation 1MHz - 11MHz

Because the graph of fig 95 shows an extremely high impedance of approximately $10\text{k}\Omega$ at around 2.7kHz the result of another run from the same building is included for comparison (fig 96). This displays another large peak at 2.7kHz , but this time only $4\text{k}\Omega$. The similarity between the plots appears to eliminate the possibility of the effect being caused by a transient signal during the measurement process. The $6\text{k}\Omega$ difference between the peaks may be due to different appliances being switched on in the house for the two measurements. Each of the peaks is associated with a negative resistance peak of approximately $1\text{k}\Omega$ at its LF side. Because these effects show a high Q they are believed to be due to resonance or standing wave effects within the wiring of the house.

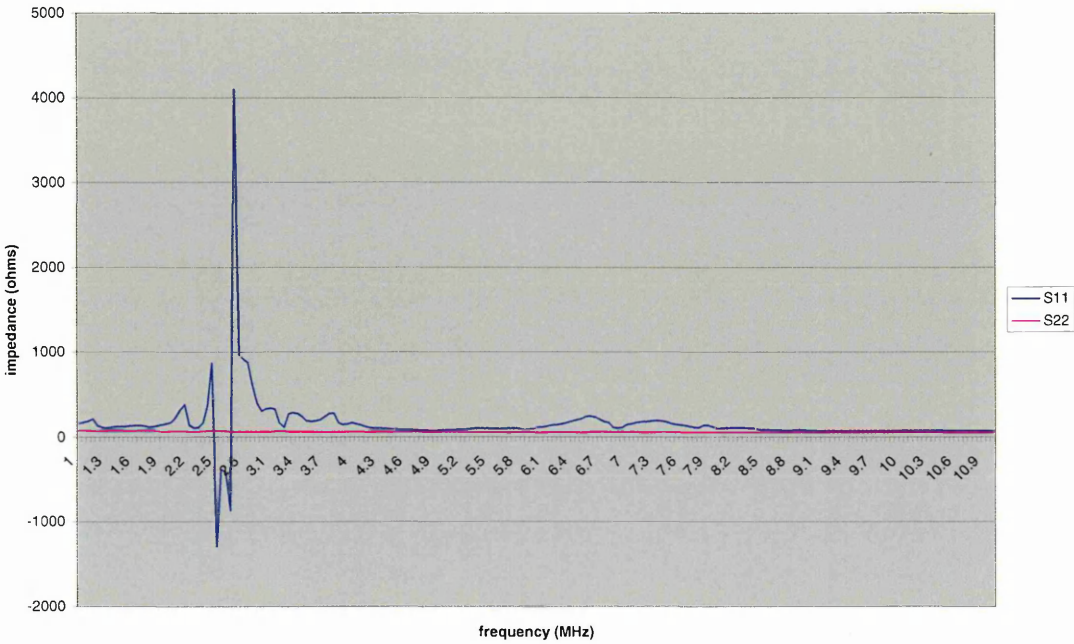


Figure 96: Impedance - houseA to link box B 1MHz - 11MHz

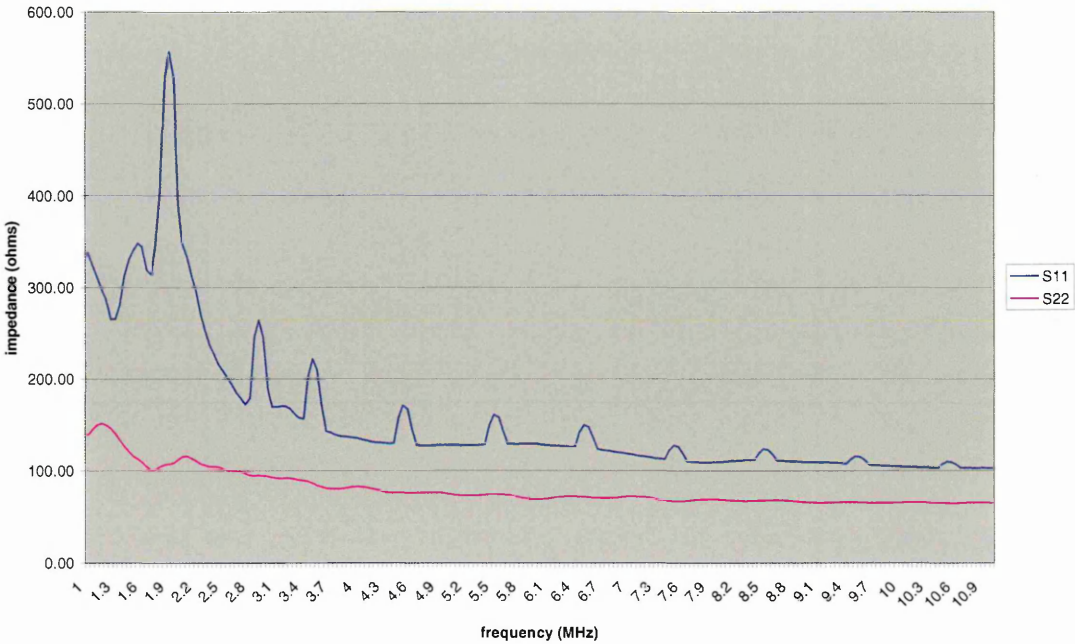


Figure 97 Impedance - substation to link Box A - PILC Cable

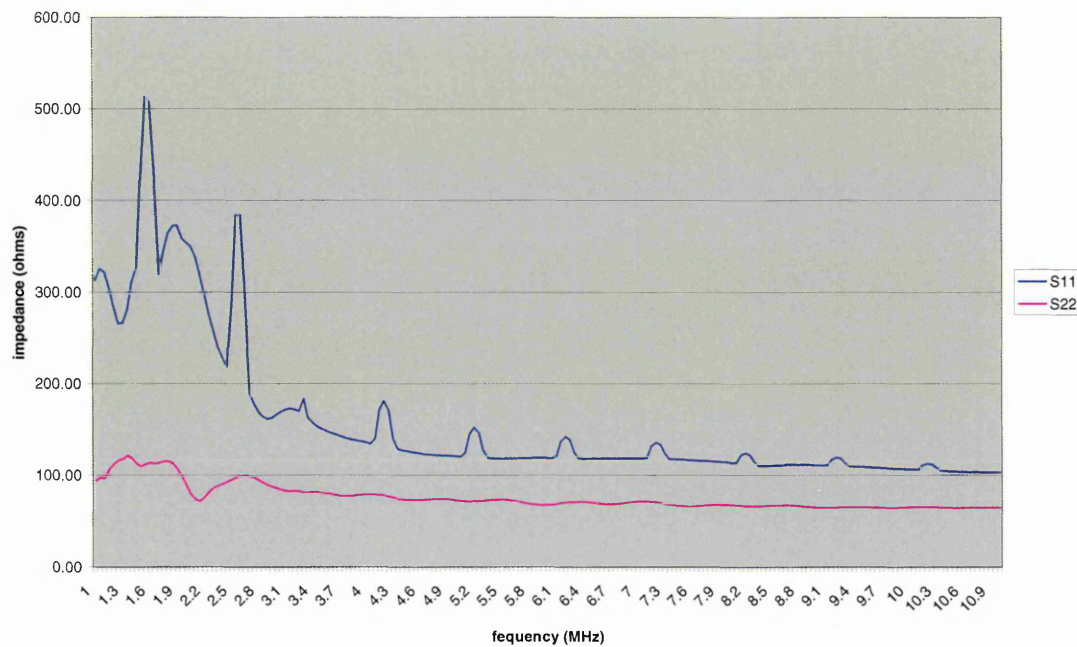


Figure 98: Impedance - substation to link box A - plastic cable

The cable to which fig 97 applies follows the same route as the cable of fig 98, but was laid more recently as part of a scheme to remove overhead lines supplying some houses in the road. The paper cable is linked through the connection box to feed house A. to which the plot of fig 96 applies.

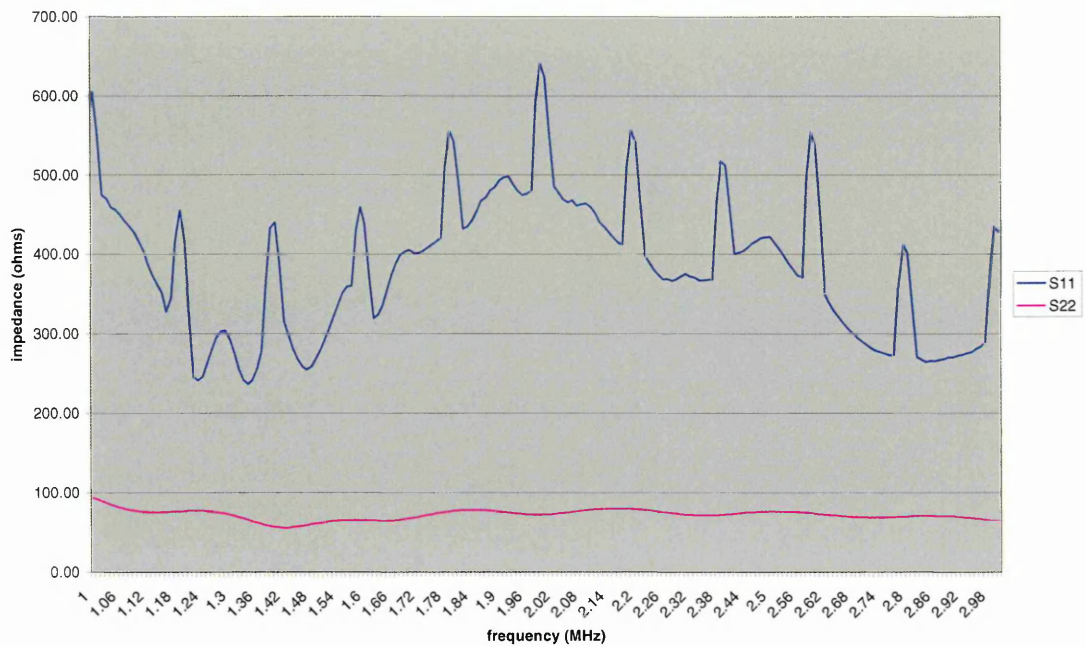


Figure 99: Impedance - house B to substation

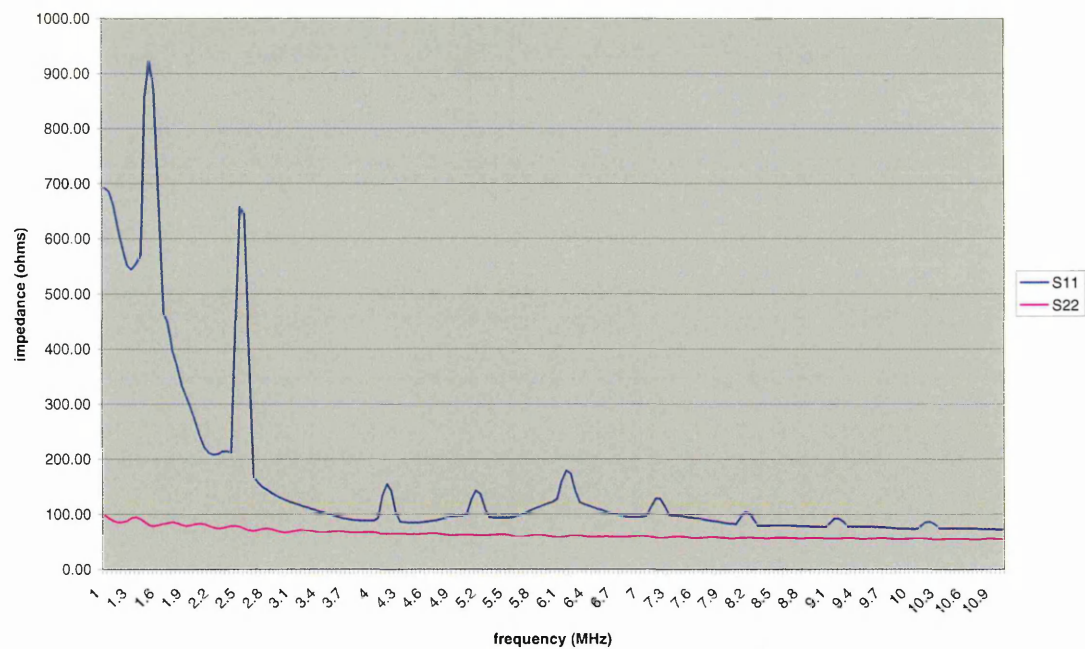


Figure 100: Impedance - overhead system - Church Close substation to The Garland Inn 1MHz to 3MHz

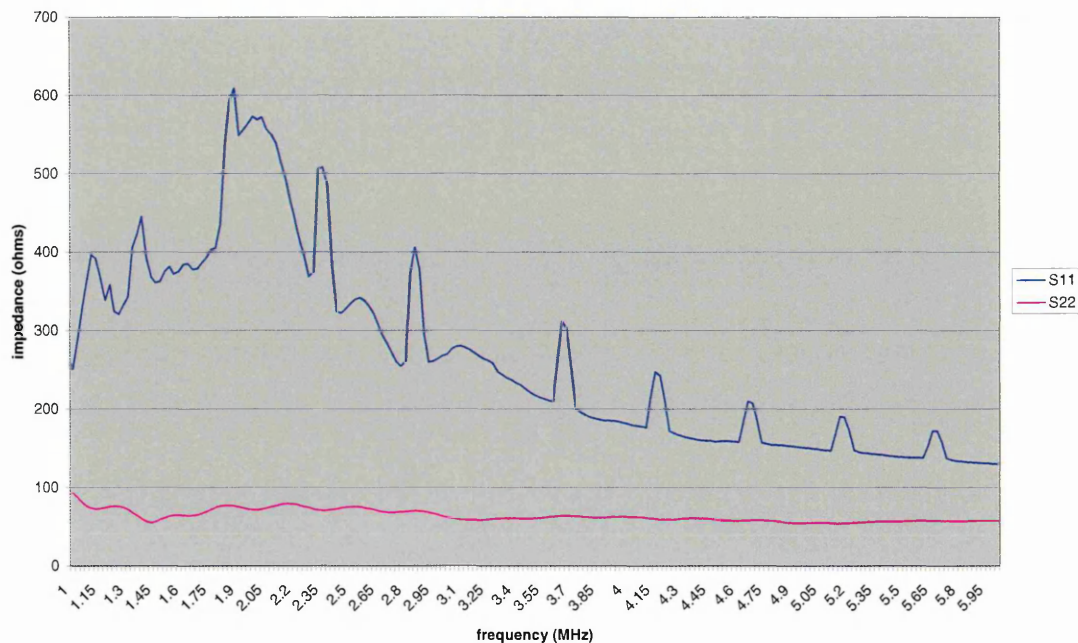


Figure 101: Impedance - overhead system - Church Close substation to The Garland Inn 3MHz to 6MHz

It should be noted that each of the plots shows far more variation of the impedance with frequency at the building than at the substation, and this is assumed to be due to the complexity of the wiring in the buildings, which provides copious opportunities for standing waves that can affect the impedance. An explanation of the reason for the smoother variation of the impedance at the substation is given in the following section.

The mean impedances and the upper and lower limits at a 95% confidence level across the measured frequency band for each test location are given in table 35.

Table 35 Mean impedances with limits

location	Frequency range (MHz)	Mean impedance (Ω)	Minimum impedance (Ω)	Maximum impedance (Ω)
House A	1 - 11	188.24	92.36	204.11
House B	1 - 11	158	135.67	180.62
Substation 1 (4 tests)	1-11	70.17	61.5	78.9
Link box (paper)	1 - 11	159.9	148.65	171.15
Link box (plastic)	1 - 11	159.56	137.9	181.22
Garland Inn (overhead)	1 - 6	267.45	71.12	72.83
Substation 2 (feed for overhead) 1-3 MHz	1 - 6	63.87	62.86	64.87

C.2 An explanation of the Difference in the Variability of the Impedance Curves between the Substation Busbars and the houses

It has been noted that the wide variations of impedance with frequency that are apparent in the measurements made at the buildings are not present at the substation busbars. This is due to an effect well known to the maintainers of radio antenna systems, which is explained in this section.

When a measurement is taken, the attenuation of the network between the point of measurement and the mismatch has an effect on the impedance seen at the measurement

point. The network attenuation increases the return loss of the mismatch, and may dominate the measurement if it is high enough. The equation for the return loss from a mismatch as seen at the measurement point in a lossy network is as shown in equation 52.

Equation 52: return loss at measurement point

$$RL = MRL + NL$$

where RL is the return loss at the measurement point, MRL is the return loss caused by the mismatch and NL is the network loss between the point of measurement and the mismatch; all expressed in dB.

The reflection coefficient can be calculated from the return loss as equation 53.

Equation 53: derivation of reflection coefficient from return loss

$$RC = 10^{\frac{\text{return_loss}}{20}}$$

and the resulting impedance of the mismatch at the measurement point is calculated as described under "Calculation of Network Impedance" in section 7.1.2.

To show how network loss affects the measurement of the effect of a mismatch at a remote point on the network, an example has been produced, based on the measurements made at house B. The model is as follows:

- The S_{11} impedance, measured at the house, was used.

- The figures for network loss were taken from other measurements performed on the network and represent the typical loss experienced on a Paper Insulated Lead Covered cable, as shown in table 36.
- It was assumed that the house closest to the substation would have 30m of network run connecting it to the substation.

Table 36: Network loss for this example

Frequency Band	Loss of 30m of PILC cable
1 - 4MHz	5.46dB
4 - 7MHz	7.3dB
7-11MHz	7.6dB

The actual impedance of the house and the calculated effect at the substation are shown in fig 102

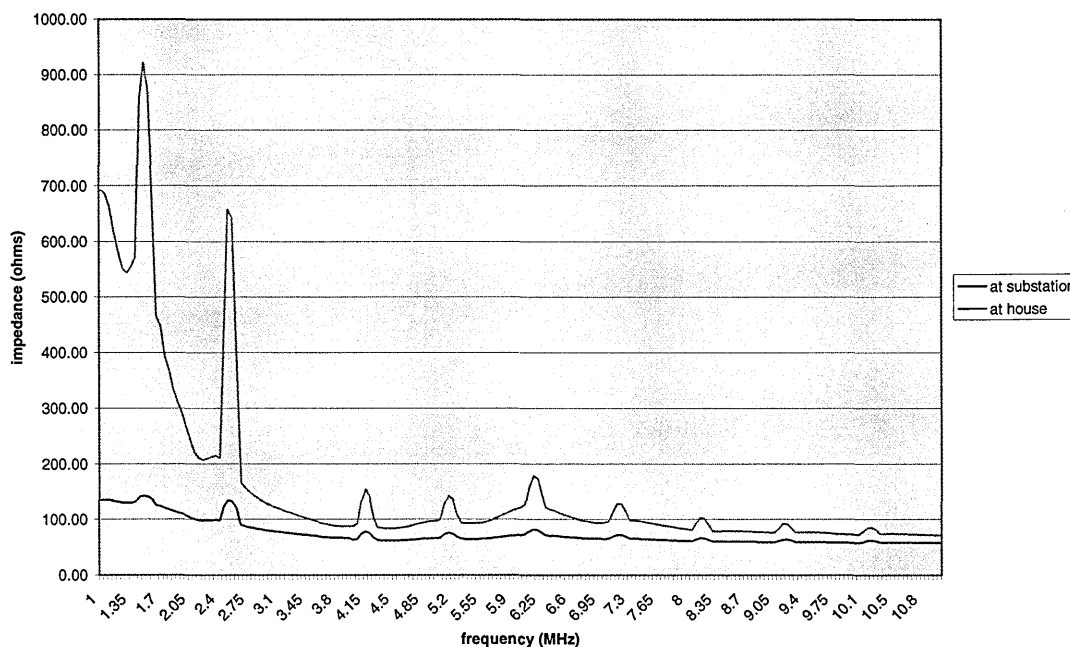


Figure 102 Effect of network loss on impedance seen at substation busbars

The mean impedance at the house is 158Ω and the mean impedance at the substation is 75.11Ω . The impedance at the substation calculated from the assumptions made in this example is similar to the impedance measured at the substation busbars, which was a mean of 70.17Ω with a range of 61.5Ω to 78.9Ω at a 95% confidence level. It can be seen that the variation in impedance at a house as seen from the substation has been smoothed by the network attenuation, as is observed in practice. Variations due to other houses more distant from the substation will be further reduced as the network attenuation will be even greater.

The same effect is not seen at the link box because the link box is closer to the buildings, being a small underground box rather than a site housing several large items of equipment.

GLOSSARY

Access system a *PLT* system used to provide access from a subscriber to the Internet or other centralized content provision, and owned by the utility company that operates the *LVDN* to which the subscriber is connected

ADSL Asymmetric Digital Subscriber Line

ADMD After Diversity Maximum Demand

ATPC Automatic Transmitter Power Control

Backhaul network the Wide Area Network linking *PLT* nodes to the *head end* or *Point Of Presence*

Band plan a statement of the way in which a radio-based service will use the available frequency spectrum

BPL Broadband Power Line - American name for *PLT*

CATV Community Antenna Television (aka Cable TV)

CDLC Cellular Data Link Control - an error correction protocol

CEB Central Electricity Board

CEGB Central Electricity Generating Board

Dark fibre an optical communications circuit in a multi-fibre cable that is rented to a third party who provides their own transmission equipment

dBm logarithmic power measurement relative to one milliwatt (1mW = 0dBm)

- dB μ V** logarithmic voltage measurement relative to one microvolt ($1\mu\text{V} = 0\text{dB}\mu\text{V}$)
- DHCP** Dynamic Host Control Protocol - a mechanism for assigning an IP address to a user who connects to a TCP/IP network
- DMT** Discrete Multi Tone - a multi-carrier modulation scheme
- DSL** Digital Subscriber Line
- DS-SS** Direct Sequence Spread Spectrum - a modulation system
- DUT** Device Under Test
- EHF** Extra High Frequency (above 900MHz))
- EHV** Extra High Voltage - $20\text{kV} < \text{EHV} < 132\text{kV}$ (OFGEM)
- EMC** ElectroMagnetic Compatibility
- FDM** a method of accommodating multiple users on a communications medium by allocating separate frequencies to different users or services
- HDSL** High-speed Digital Subscriber Line
- Head End** the Internet Service Provider's source of content or connection to the Internet of a PLT or CATV system
- HF** High Frequency - 3MHz - 30MHz
- Hop** one one link in the PLT system, eg between two repeaters. A route between the subscriber and the node may consist of several hops
- HV** High Voltage - $1\text{kV} < \text{HV} < 20\text{kV}$

IMP Intermodulation product

Ingress noise unwanted signals on a PLT or CATV system
resulting from reception of broadcast radio signals
on connected wiring and cabling

In-house system a PLT system used within a building
to provide LAN services, multi-media distribution
etc, and owned and operated by the owner of the
building

ISP Internet Service provider

K factor measurement parameter relating the radiated
emissions from a structure with wiring connected to
a PLT system to the injected power from the PLT
modems

LAN Local Area Network

LCL Longitudinal Conversion Loss

LISN Line Impedance Stabilisation Network

LV Low Voltage - below 1000V (OFGEM)

LVDN Low Voltage Distribution Network - the network
operated by the utility company to provide
electricity to customers

Mbps Megabits per second

MV Medium Voltage - above 1000V and below 100kV (term
not used by the UK electricity Supply Industry)

NGC National Grid Company

Node The location containing the transmission equipment
connecting the PLT LAN to the head-end equipment

- Notches** gaps created in the output spectrum of a PLT modem to protect various types of radio services, eg amateur or emergency service bands
- OFCOM** UK communications and broadcasting regulatory body
- OFDM** Orthogonal Frequency Division Multiplexing - a multi-carrier modulation scheme
- OFGEM** UK electricity supply regulators office
- OPERA** Open PLC European Research Alliance
- PILC** Paper Insulated, Lead Covered; a form of distribution mains cable construction
- PLT** Power Line Telecommunications
- POP** Point Of Presence - the place at which an ISP connects to the Internet
- Protection ratio** the signal to noise ratio between the minimum wanted signal and the maximum unwanted signal in an interference limited radio band plan
- PSCRG** (Open University) Power Systems Communications Research Group
- PSD** Power Spectral Density
- PTT** Post, Telephone and Telecommunications provider (aka telco)
- REC** Regional Electricity Company
- SDH** Synchronous Digital Hierarchy
- SONET** Synchronous optical Network

- Spinning reserve** generating Plant under steam but not exporting power, ready for instant deployment to meet an unexpected demand peak
- SSE** Scottish and Southern Energy
- Substation** a transformer point on the utility company network at which a voltage change occurs
- TCP/IP** Transmission Control Protocol/Internet Protocol
- TDM** Time Division Multiplexing - a method of allowing multiple use of a single communications medium by allocating separate time slots to different users
- Unit protection** a method of clearing faults from the power network in which the current entering the protected section is compared with the current leaving it. Even if the current is excessive the switchgear will not trip out the circuit if the incoming and outgoing currents are the same, because that means that the fault is outside the protected section. Unit protection requires a communications circuit between the substations at the two ends of the protected cable.
- VoIP** Voice over Internet Protocol - a mechanism for transmitting speech signals via data networks
- VSAT** Very Small Aperture Terminal - a private satellite system using dish antennas of between 1m and 3.7m.diameter at the remote terminals
- WAN** Wide Area Network

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